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CERAMIC HIGH PRESSURE GAS PATH SEAL

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)  Stage 1 ceramic shrouds (high pressure turbine gas path seal) were developed for the GE T700 turbine helicopter engine under the Army/NASA Contract NAS3-23174. This contract successfully proved the viability and benefits of a Stage 1 ceramic shroud for production application. Stage 1 ceramic shrouds were proven by extensive component and engine testing. This Stage 1 ceramic shroud, plasma sprayed ceramic ( $ZrO_2-8Y_2O_3$ ) and bond coating (NiCrAlY) onto a cast metal backing, offers significant engine performance improvement. Due to the ceramic coating, the amount of cooling air required to cool the Stage 1 shroud is reduced 20% resulting in a 0.5% increase in horsepower and a 0.3% decrease in specific fuel consumption. This is accomplished with a part which is lower in cost than					
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the current production shroud. Stage 1 ceramic shrouds for the GE T700 engine will be introduced into field service in the 3rd Qtr 1987. This is the first production application for a ceramic shroud in a GE production turbine engine.

## PREFACE

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## 1.0 INTRODUCTION

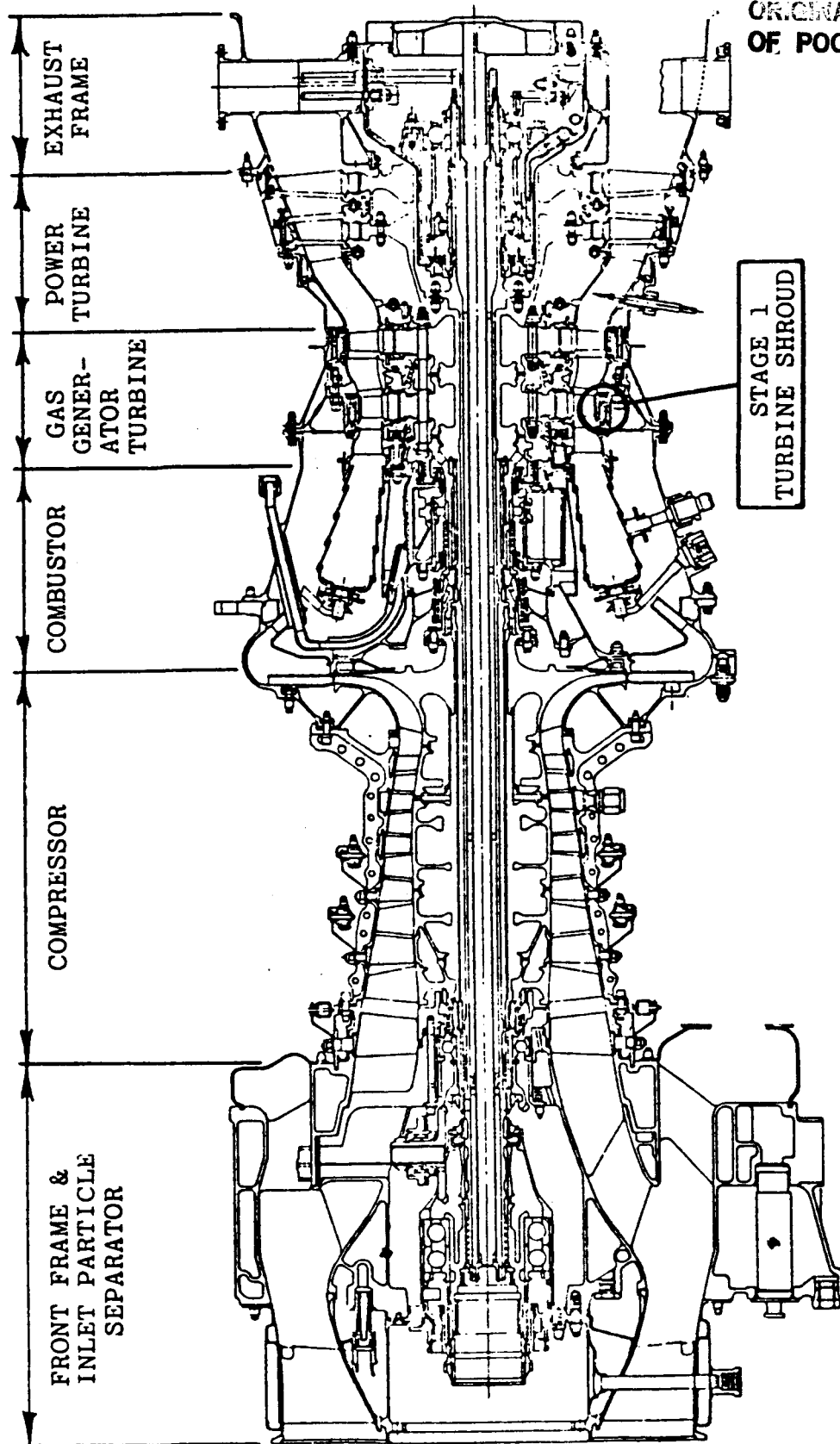
Gas turbine performance is greatly influenced by blade tip-to-shroud gas leakages, along with shroud cooling air requirements. Blade tip-to-shroud leakages can be minimized and cooling air requirements can be reduced by the introduction of stable, rub-tolerant, durable and low thermal conductivity materials. Presently, plasma-sprayed oxide ceramics (stabilized zirconia) offer the capability to achieve these goals. Oxide ceramics such as zirconia ( $ZrO_2$ ) flowpath surfaces when suitably secured to plasma-sprayed bond coat surfaces offer unique High Pressure Turbine (HPT) shroud capabilities. This ceramic material can yield dimensionally stable structures, can operate with less cooling, and can provide thermal shielding of the underlying structures, at a cost which is the same as or lower than the best known metallic shroud materials.

Under Army/NASA Contract NAS3-23174 a ceramic-coated shroud was developed which meets the above goals for production introduction on the General Electric T700 Helicopter Turbine Engine.

### 1.1 SUMMARY

This report summarizes the accomplishments of the Army/NASA Contract No. NAS3-23174 for the Small General Electric T700 Helicopter Turbine Engines. This program successfully developed and demonstrated, for production application, the viability of a ceramic thermal-barrier coating applied to a metal alloy Stage 1 high pressure turbine shroud seal, as shown in Figures 1-1, 1-2, and 1-3.

The type of ceramic coating which is the most durable and cost effective in the T700 operating environment is a sintered zirconium oxide-yttrium oxide powder ( $ZrO_2-8Y_2O_3$ ) which is applied by an air plasma-sprayed process developed by General Electric. The General Electric Company is the production ceramic coating source and has been fully qualified.



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Figure 1-1. T700-GE-700/-401 Engine.

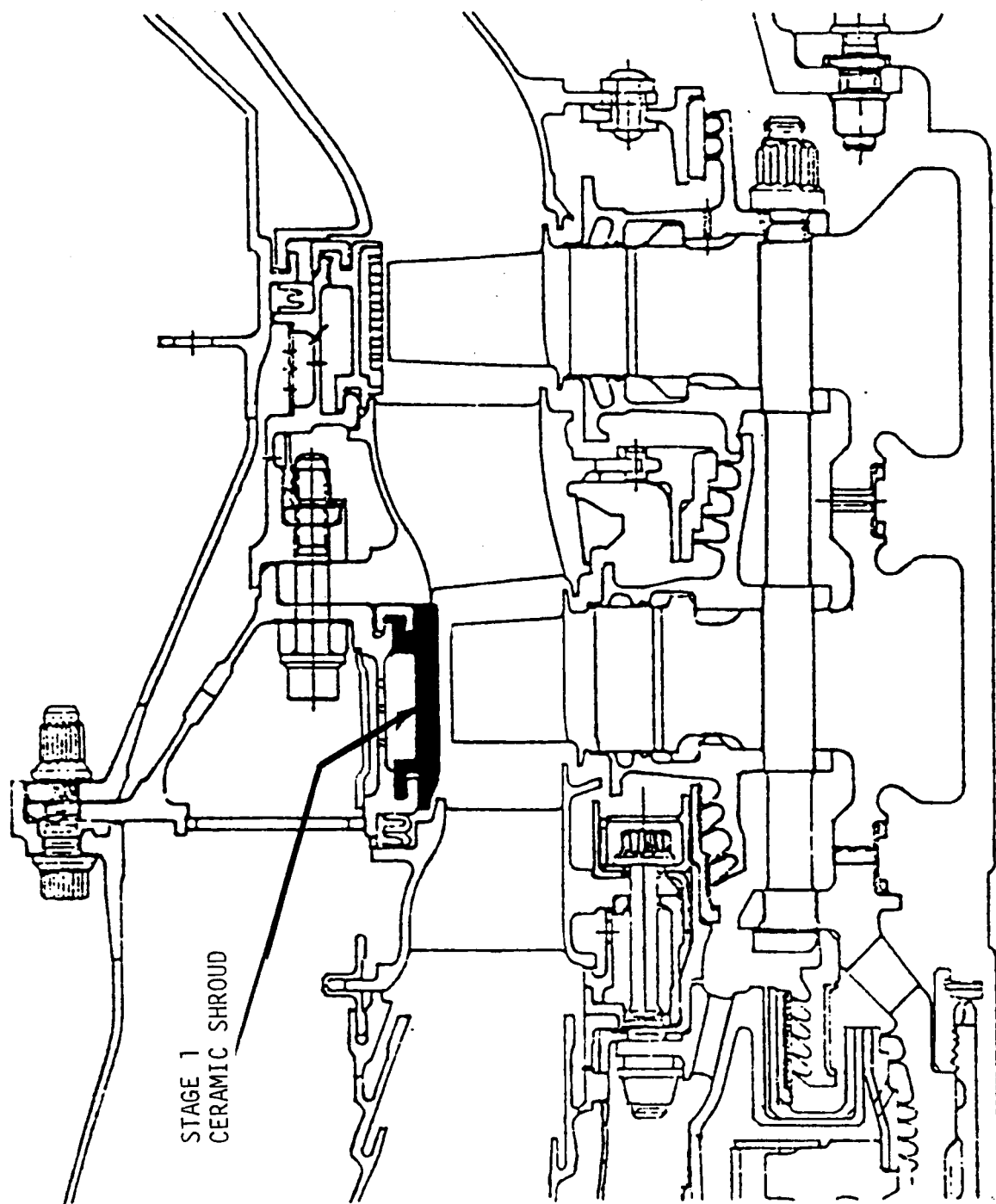


Figure 1-2. T700-GE-700/-401 Engine Gas Generator Turbine.

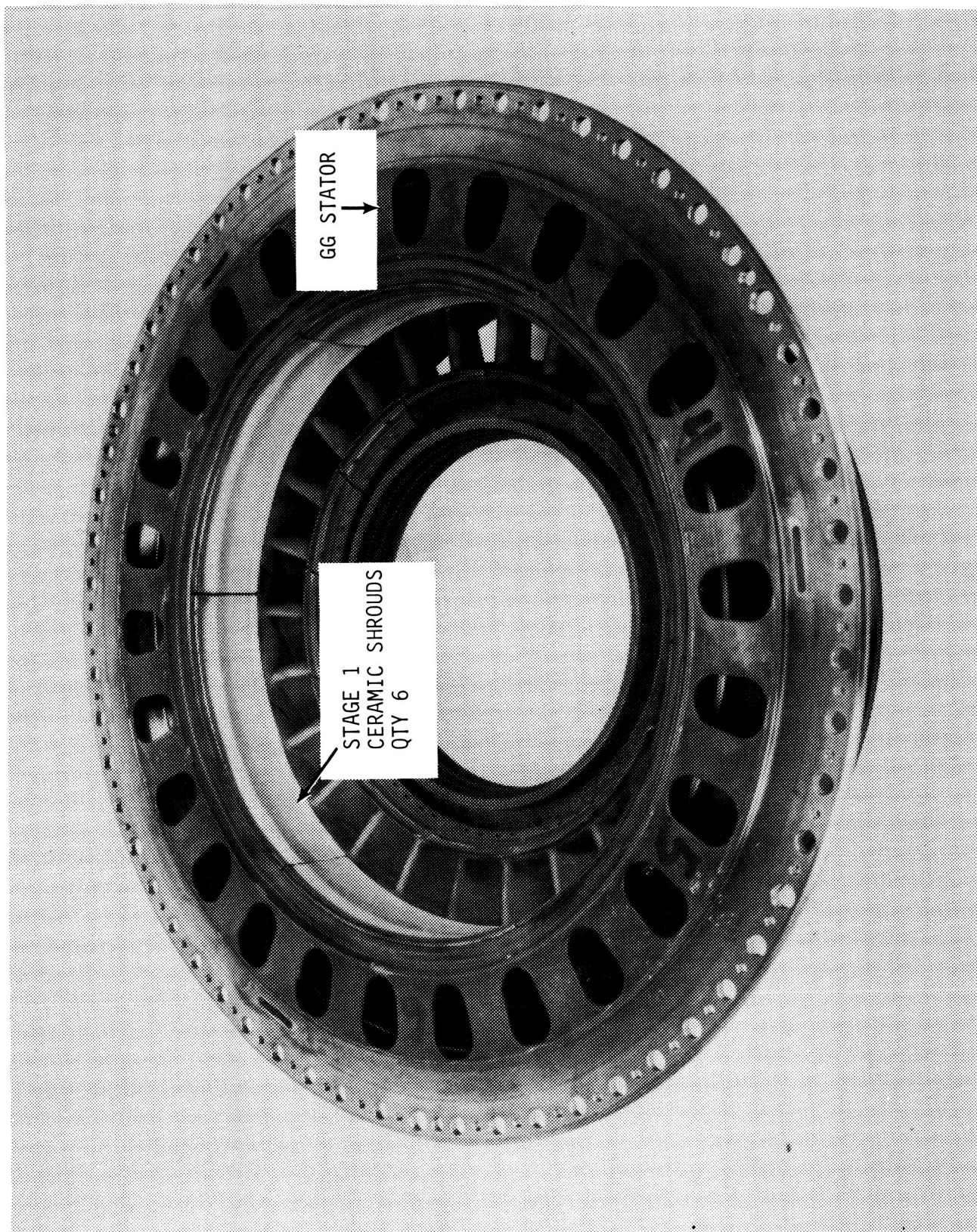


Figure 1-3. GG Stator and Stage 1 Ceramic Shrouds.

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The new production Stage 1 shroud system for the T700 engine is shown on Figure 1-4. The Stage 1 ceramic shroud consists of a cast INCO 738 backing, which is common with the current production shroud. The cast backing is machined and then a 10 mil bond coat is applied. On top of the bond coat the ceramic coating is applied. After the shrouds are assembled into the Stage 1 shroud support, the ceramic is ground to final inner diameter, leaving a coating thickness of about 30 mils. The Stage 1 shroud support is a fabricated structure of INCO 718 and INCOLOY 903. The configuration of the Stage 1 shroud support is unchanged over the current production, except for a reduction in the number of cooling holes, which reduces shroud cooling flow by 20%.

Shown in Figure 1-5 is a comparison of the current production shroud systems and the new ceramic shroud. The ceramic shroud is fully interchangeable with all the current production shroud systems. The cast INCO 738 backing structure is common with the solid Stage 1 shroud.

A comparison of the characteristics of the ceramic shroud to the current production shrouds as shown in Table 1-1 clearly shows the benefit of the ceramic shroud. The ceramic shroud is better than all the current production designs in characteristics which affect performance and life except for erosion resistance. The erosion of ceramic shrouds would only occur in extremely severe sand environments. Ceramic shrouds were engine sand erosion tested along with the current production designs as described in this report.

The major proven benefit which ceramic shrouds offer over the current production T700 Stage 1 shroud is a reduction in shroud cooling air requirements, due to the insulating ability of the ceramic coating. A reduction in shroud cooling air levels improves the efficiency of the high pressure turbine. The T700 Stage 1 ceramic shrouds were qualified for production with a 20% reduction in cooling level. Reducing the Stage 1 shroud cooling flow by 20% increases engine SHP at IRP by .5% and reduces SFC at 60% MC by .3%. This improvement in engine performance is accomplished with a ceramic shroud which is lower in cost than the current production stage 1 shroud and is fully compatible with the current production shroud support.

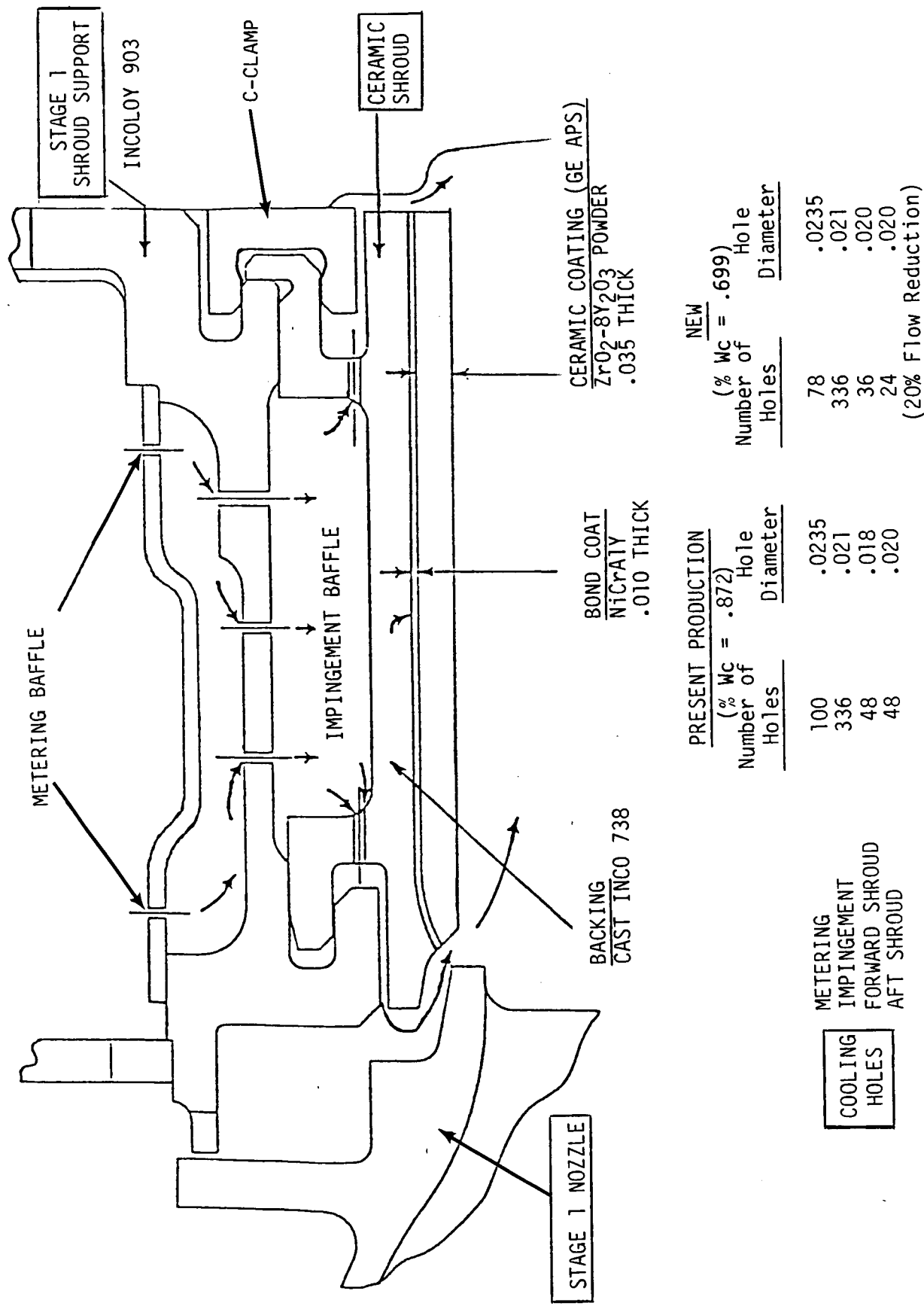
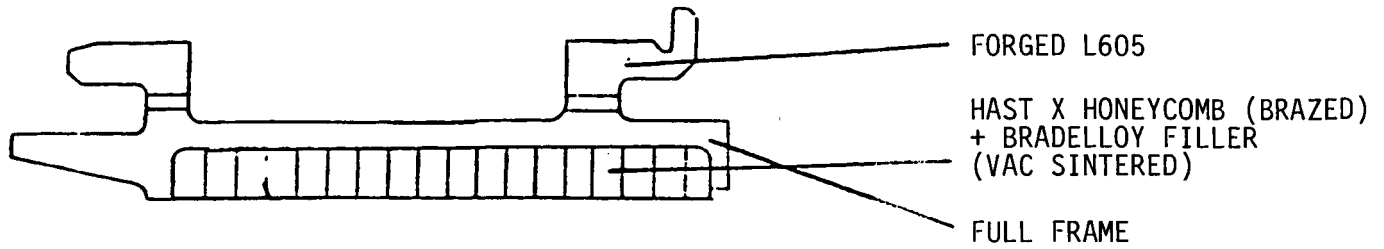
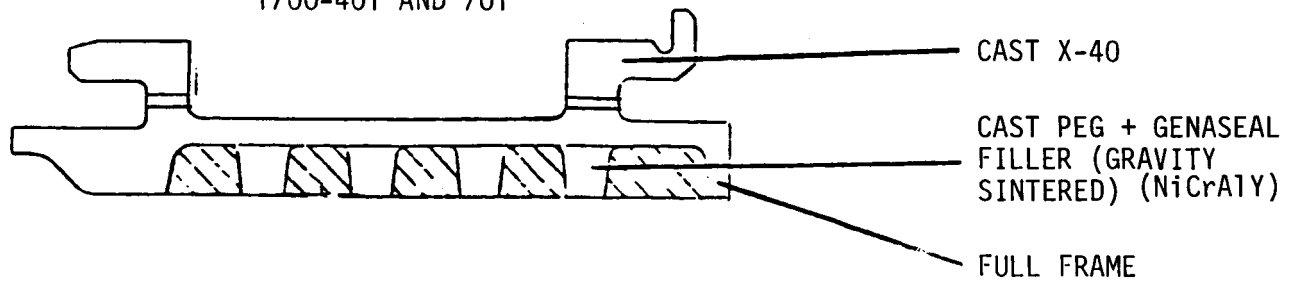


Figure 1-4. Ceramic T700 High Pressure Turbine Stage 1 Shroud Design  
(Production Configuration).

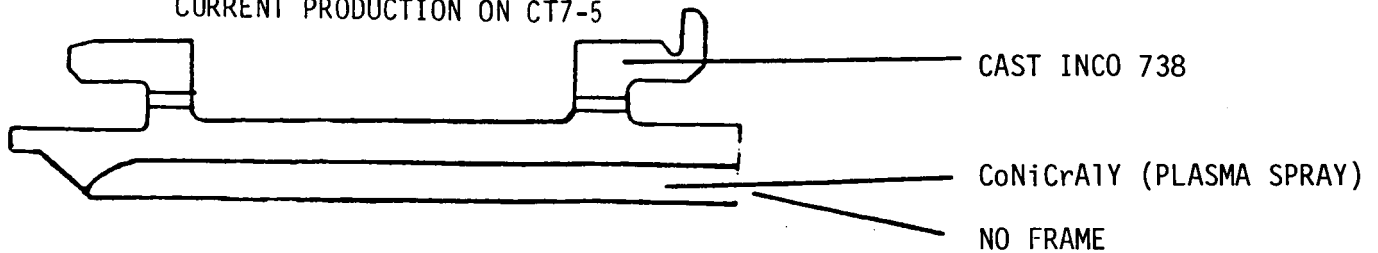
BRADELLOY  
CURRENT PRODUCTION ON T700-700



GENASEAL  
CURRENT PRODUCTION ON  
T700-401 AND 701



SOLID  
INTRO 1987 ON T700-701  
CURRENT PRODUCTION ON CT7-5



CERAMIC  
INTRO SEPTEMBER 1987 ON T700-401

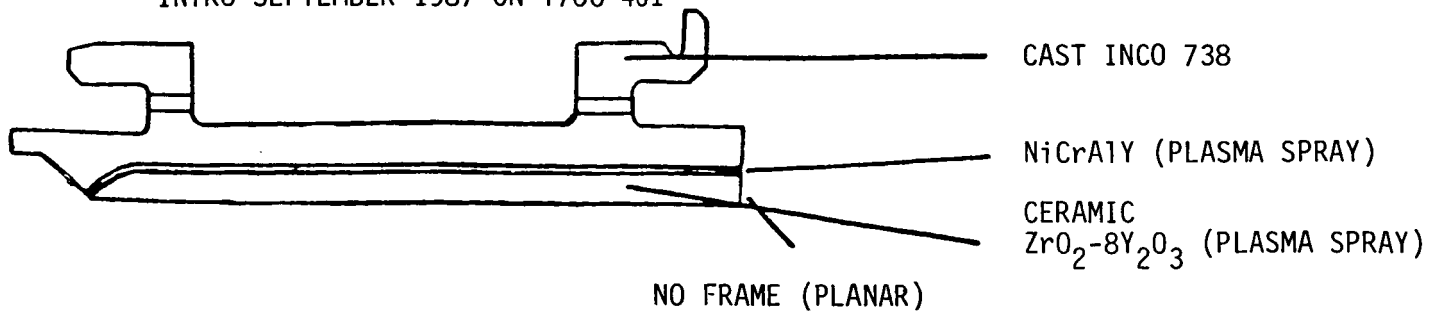


Figure 1-5. Ceramic vs Bradelloy, Genaseal and Solid Shrouds.



TABLE 1-1. Shroud Property Comparison.

<u>CHARACTERISTIC</u>	<u>BRADDELLOY</u>	<u>GENASEAL</u>	<u>SOLID</u>	<u>CERAMIC</u>	<u>IMPACT OF CERAMIC</u>
• Swelling	High (and Erratic)	High	Low	[Lowest]	Tighter blade/shroud clearances
• Oxidation Resistance	Low	Moderate	Good	[Best]	Improved durability
• Thermal Conductivity	Moderate	High	High	[Very Low]	Reduced shroud cooling or reduced shroud and support temperature. Performance improvement.
• Erosion Resistance (Component Tests)	Low [Best in Engine Test]	Moderate	[High]	Moderate (Lowest in Engine Test)	Performance retention
• Cost	Moderate	High	Low	Low	Similar to Solid
• Shroud Grind Flexibility	[High]	High	Low	Lowest	- - - -
• Grind Method	ECG or Mech	ECG or Mech	ECG or Mech	Mech Only	- - - -
• Durability (Engine Test Results)	Lowest	Good	Better	[Best]	Lower life cycle cost
• Repairability	Moderate	Poor	Good	[Good]*	Lower life cycle cost
• Blade Rub Characteristics	Poor	Poor	Poor	Poor	All shrouds wear blades

[ ] = Best

\* Not Demonstrated

A comparison of the cost of the current production shrouds to the ceramic shrouds is shown in Table 1-2.

TABLE 1-2. Production Cost (250th Unit) of Ceramic vs Current Production.

All of the parts have six segments per engine set.

	<u>Shop Cost (Per Engine Set)</u>
1. Genaseal, 6053T22G02	\$1838 - Actual
2. Bradelloy, 6039T07G02	\$1531 - Actual
3. Solid, 6055T58P01	\$1383 - Actual
4. Ceramic, 6064T52P01 GE Coating	\$1476 - Estimate*

Notes:

We have an opportunity for further cost reduction of Ceramic Shrouds by reduction of current inspection cost. Manufacturing inspection cost of ceramic shrouds is currently high due to the new manufacturing processes.

\* Based on actual vendor quotes for production shrouds

The viability and benefit of the T700 Stage 1 ceramic shrouds were proven by the successful completion of three phases of the Army/NASA contract NAS3-23174. A summary of the work completed under the three phases of this program is as follows:

Phase I - Development of Manufacturing Process

- Task I - Detail Design and Analysis:

- Selected the initial ceramic shroud materials (ceramic coating, bond coating and backing). For these materials the initial process specifications were determined.
- Determined the initial quality assurance requirements which defined the acceptable material and processing parameters.
- Completed analysis of transient and steady state ceramic shroud temperatures and thermal stresses.

- Completed the initial ceramic shroud drawings which will be used to manufacture the first sets of ceramic shrouds.
- Completed the initial life cycle cost analysis of the ceramic shrouds.
- Task II - Manufacture Facility Setup and Process Development:
  - Determined and completed the tooling to plasma spray the ceramic and bond coating and to machine the shrouds. Test coupons which were used to verify the manufacturing process were completed.

## Phase II - Full-Scale Hardware Fabrication

- Task III - Fabricate and Verify Full-Scale Components:
  - Completed the manufacture of ceramic shrouds produced using three different ceramic shroud processes:
    1. Vacuum Plasma Deposition NiCrAlY bond coat and composite (ceramic)  $ZrO_2-8Y_2O_3$  powder process (GE-VPD). Shroud coating applied by General Electric.
    2. Air Plasma-Sprayed NiCrAlY bond coat and sintered (ceramic)  $ZrO_2-8Y_2O_3$  powder heat-treated top coat process (GE APS). Shroud coating applied by General Electric.
    3. Shielded Arc Plasma CoNiCrAlY bond coat and fused (ceramic)  $ZrO_2-7Y_2O_3$  powder heat-treated top coat process (UC-SAP). Shroud coating applied by Union Carbide.
  - Successfully completed thermal shock testing of the three types of ceramic shrouds under engine temperature conditions.
  - Ordered ceramic shrouds made from the three ceramic shroud processes for engine testing in Phase III.
- Task IV - Update Specifications and Cost Estimates
  - Specifications and cost estimates were updated to reflect the planned final ceramic shroud design.

## Phase III - Pilot Production and Qualification Testing

- Task V - Preparation of Hardware for Engine Test:
  - Ceramic shrouds were ordered for LCF and endurance engine testing.
- Task VI - Engine Tests:
  - Extensive engine testing was completed on the ceramic shrouds which proved the integrity and performance benefit of ceramic shrouds. All three types of ceramic coatings were engine tested (GE VPD, GE APS and UC SAP).

The GE APS coated shroud proved to be the most durable system engine tested and is the lowest-cost coating system. Based on these attributes, GE APS was selected for the qualification engine testing. The GE APS shrouds were in excellent condition after qualification engine test as determined by extensive metallurgical examination.

### 1.2 Major Accomplishments of Army/NASA Contract No. NAS3-23174

1. Development of ceramic coating and bond coating combination material which is durable, producible and cost effective.
2. Development of ceramic coating and bond coating production application techniques which consistently apply the ceramic and bond coatings in a manner which provides high durability.
3. Completion of extensive Laboratory thermal shock testing which helped to determine the best ceramic coating technique prior to engine testing. Viability of thermal shock testing to determine the integrity of the ceramic coating was proven by correlation of thermal shock testing with engine testing results.
4. Completion of extensive heat transfer and 3-D finite element stress analysis.
5. Successful manufacture of ceramic shrouds using production processes.
6. Completion of extensive engine testing, both endurance and low cycle fatigue, which proved the integrity and viability of ceramic shrouds. (See Table 1-3.)
7. Successful qualification engine test of ceramic shrouds, which will lead to production introduction by June 1987.

### 1.3 Areas for Further Improvement

1. Heat transfer and 3-D Stress analysis must be improved to adequately predict the life of the ceramic shrouds.
2. Methods must be developed to nondestructively examine the integrity of the ceramic coating.
3. After engine testing the ceramic shrouds are not completely crack-free, although minor cracking of the ceramic coating did not affect the integrity of the ceramic.
4. Erosion resistance of ceramic shroud as proven by engine testing is not as good as current production shroud types.

TABLE 1-3. Summary of Engine Testing (Phase III, Task VI).

Engine Serial Number	Type of Test	Endurance Hours	Total Hours	Purpose of Test	Type of Shrouds	Type of Shroud Support	Remarks
374117-1	Assurance	3300 LCF Cycles	398	Tested 3 types of ceramic flowpath coatings; 20% reduction in shroud cooling	2 GE APS 2 GE VPD 2 UC SAP (Dev. Parts)	20% reduction in cooling	<ul style="list-style-type: none"> <li>• GE APS performed well and better than other types</li> <li>• GE VPD ceramic shrouds - lost ceramic on trailing edge; dropped out of program.</li> </ul>
212108-4	Assurance	300	560	Tested 2 types of ceramic flowpath coatings	3 GE APS 3 UC SAP (Dev. Parts)	No reduction in cooling	<ul style="list-style-type: none"> <li>• Shrouds in excellent condition (GE-APS and UC-SAP excellent)</li> <li>• GE-APS suffered assembly damage which did not lead to ceramic failure</li> </ul>
374117-3	Assurance	3300 LCF Cycles	450	Tested 2 types of ceramic flowpath coatings	3 GE APS 3 UC SAP (Dev. Parts)	No reduction in shroud cooling	<ul style="list-style-type: none"> <li>• Shrouds in good condition</li> <li>• GE shroud had minor side spall on ceramic but did not propagate</li> </ul>
372516-3A	Qualification	300	403	To demonstrate performance improvements	6 GE APS (Prod. Parts)	20% reduction in cooling	<ul style="list-style-type: none"> <li>• All shrouds in excellent condition even after stage 1 blade failure</li> </ul>
207018-8	Assurance Sand Ingestion	60		To determine erosion capabilities of ceramic coatings vs current production shrouds	2 GE-APS 2 Solid 2 Bradelloy (Prod. Parts)	No reduction in cooling; standard production	<ul style="list-style-type: none"> <li>• Turbine performance acceptable after sand ingestion</li> <li>• Ceramic eroded more than current production but still acceptable</li> </ul>

## 2.0 PHASE I - DEVELOPMENT OF MANUFACTURING PROCESS

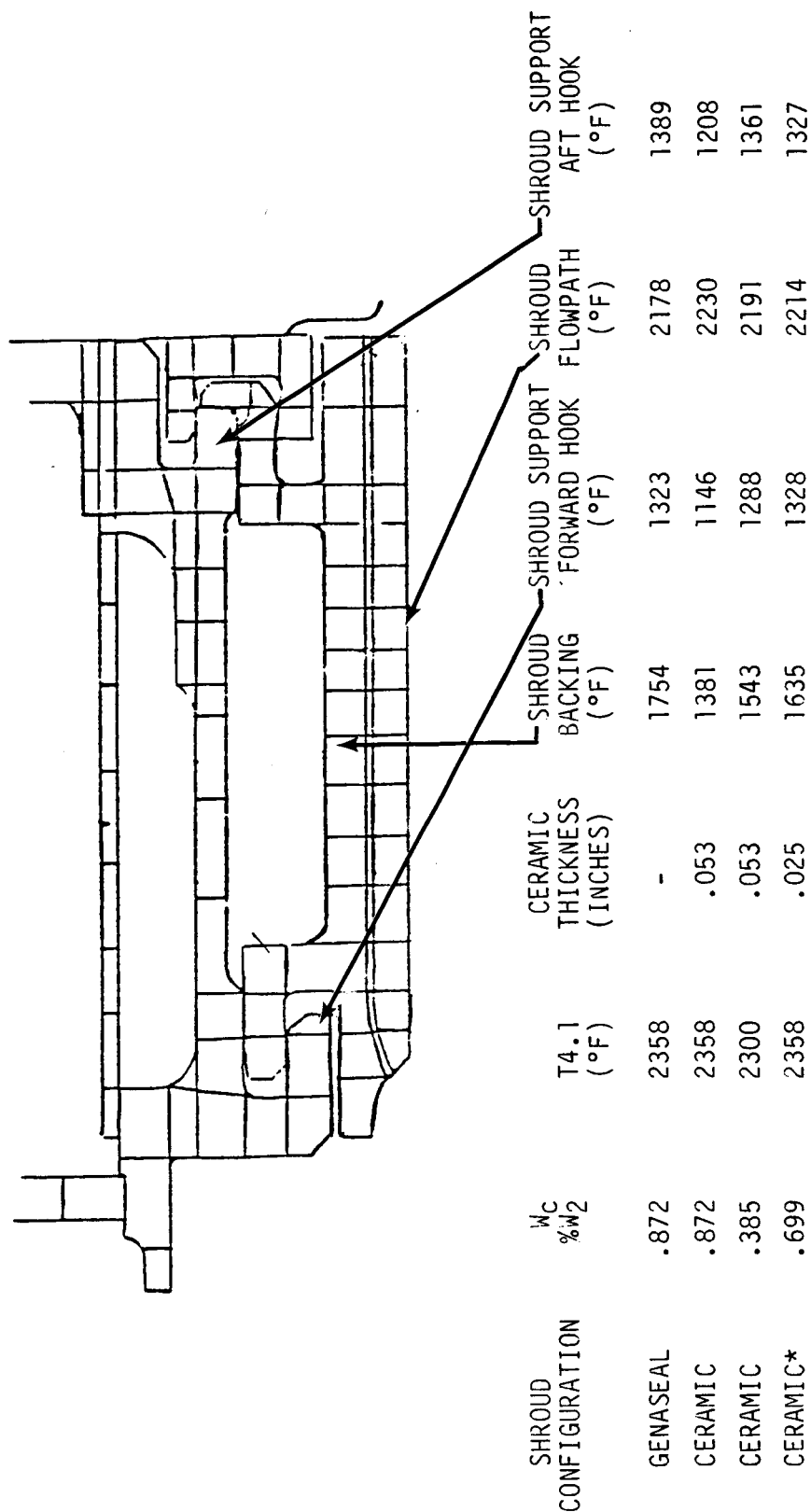
### 2.1 TASK I - DETAIL DESIGN AND ANALYSIS

#### 2.1.1 Heat Transfer and Thermal Stress Analysis

Steady-State and transient heat transfer analysis was performed on each element of the ceramic shroud system (i.e., shroud backing and rail support, ceramic bond coat and ceramic top coat). Shown in Figure 2-1 are the maximum steady-state temperatures of the ceramic shroud flowpath, shroud backing and shroud support rails. For the ceramic shroud with the same cooling flow as the current production Genaseal shroud (.872% Wc), the shroud backing and shroud support are considerably cooler due to the insulating ability of the ceramic material. When the cooling flow is reduced 20% down to .699% Wc (planned production ceramic shroud cooling flow), the shroud backing and support structure remain as cool as the Genaseal shroud at the higher cooling flow. The analysis with .699% Ws was accomplished at the minimum ceramic thickness of .025 inches which can occur in an engine after assembly grinding the ceramic flowpath surface.

The transient thermal analysis of the ceramic shroud (as shown in Figures 2-2 through 2-4) was accomplished with a .053-inch thick ceramic coating and .385% Wc cooling flow. These values of ceramic coating thickness and cooling flow were selected for the purpose of analysis because they represented the maximum anticipated capability of the shroud system (i.e., maximum ceramic material thickness and minimum cooling flow). This combination of ceramic thickness and cooling flow produced steady-state temperatures which are close to the final production design temperatures (see Figure 2-1). Therefore, transient heat transfer analysis performed at this ceramic coating thickness and cooling flow is a reasonable approximation of the expected temperature conditions in the ceramic shroud.

The ceramic shroud was extensively analyzed using the above transient temperature analysis to determine thermal strains in the ceramic coating using finite element methods in two steps. First, a 2-D axisymmetric shell



\*Final Production Design

Figure 2-1. Steady-State Temperatures.

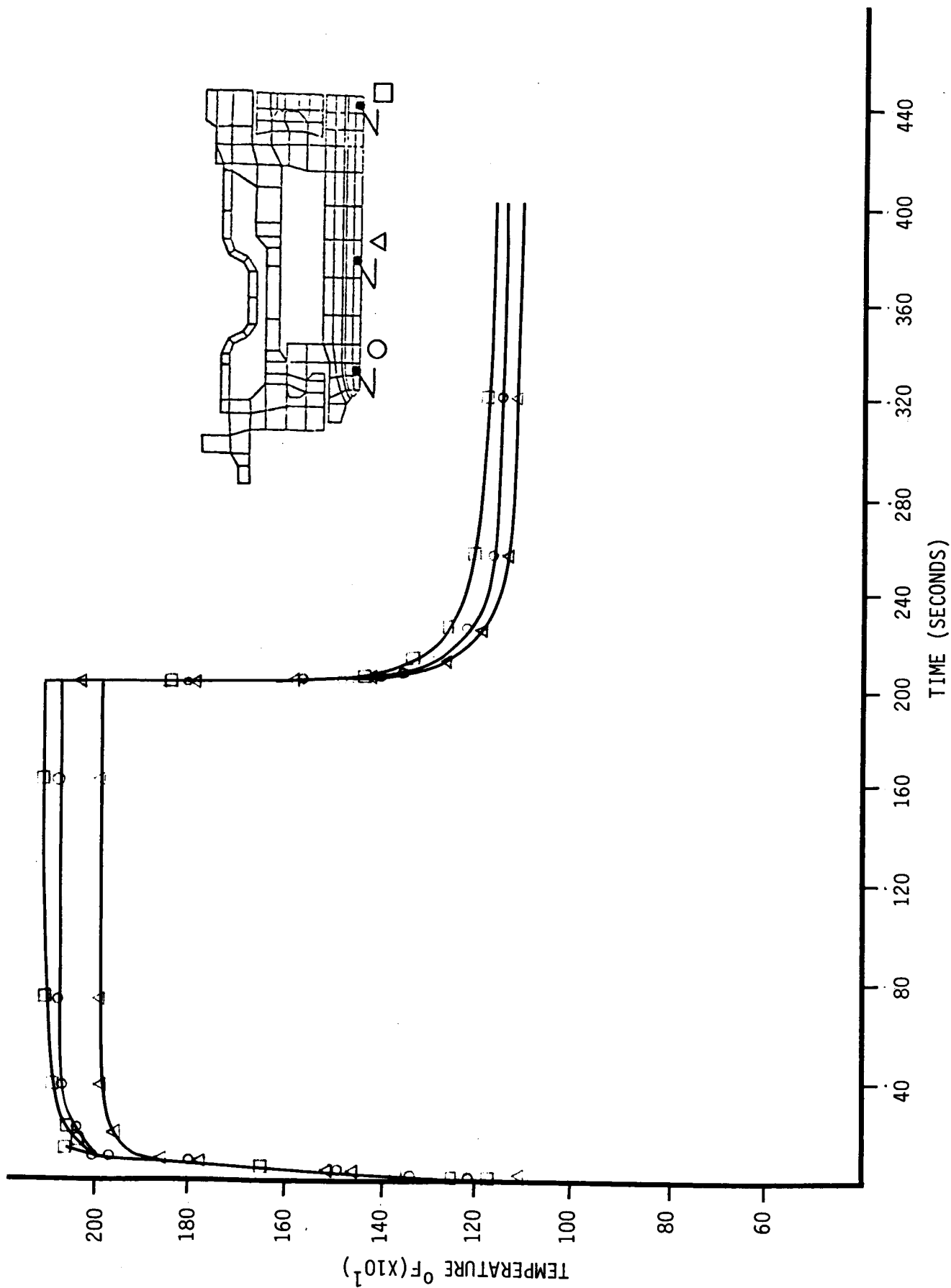


Figure 2-2. Ceramic Top Coat Transient Temperatures.



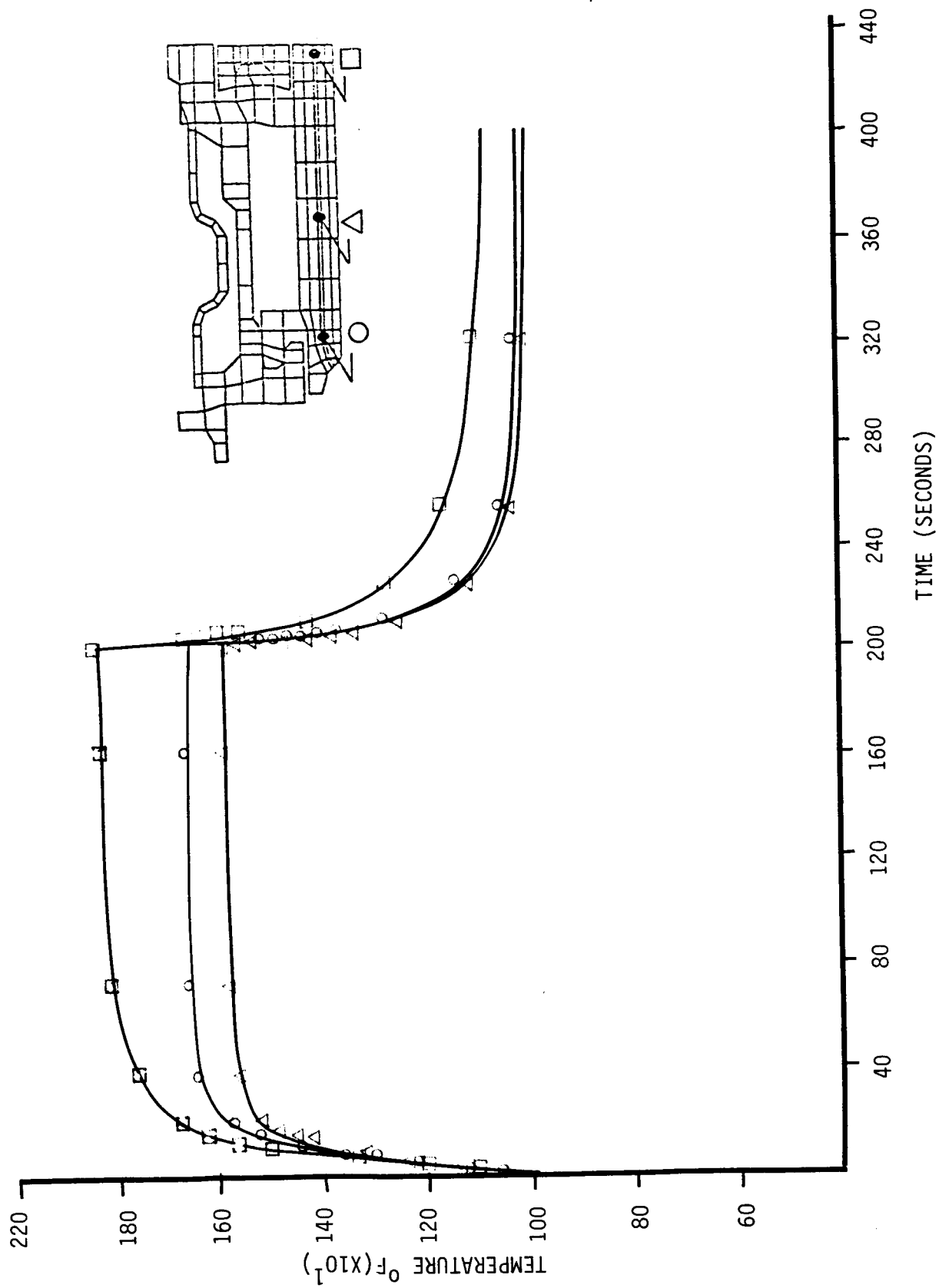


Figure 2-3. NiCrAlY Bond Coat Transient Temperatures.

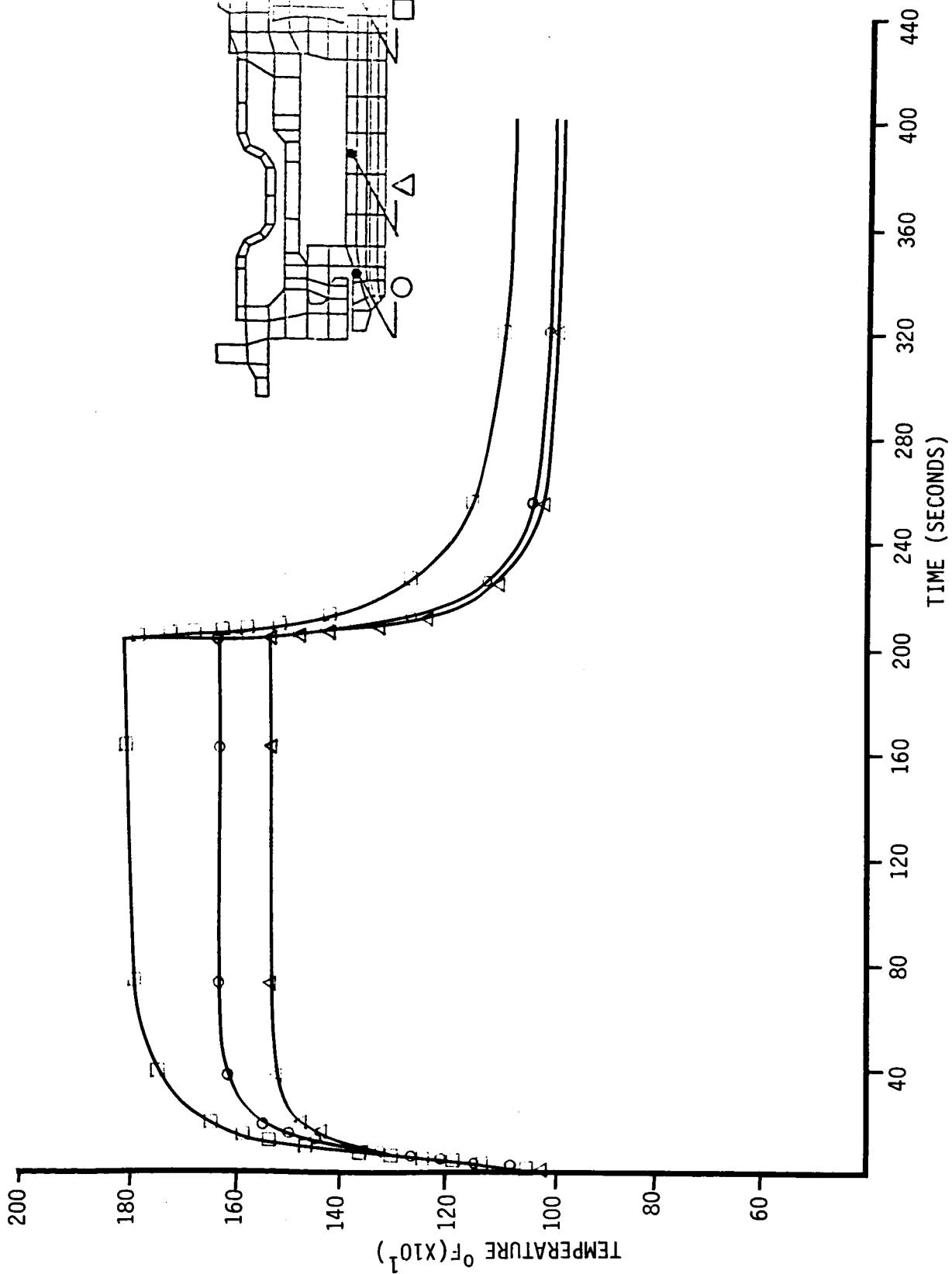


Figure 2-4. Shroud Backing Transient Temperatures.

CLASS/MASS model of the shroud support structure and ceramic shroud was generated to calculate the displacement boundary conditions applied to the ceramic shroud for various transient time steps. This 2-D finite element model is shown in Figure 2-5. The shroud portion of the 2-D CLASS/MASS model was analyzed using orthotropic material properties (shell elements without hoop stress capability) to simulate the effects of discrete shroud segments on the support structure. The displacements of the shroud-support interface were calculated for each of eight time steps:  $t=0$  (idle);  $t=5, 9$  and  $35$  seconds (transient burst);  $T=200$  (steady state max);  $t=200, 225$  and  $255$  seconds (transient chop). The support/shroud displacement boundary conditions generated from the 2-D finite element analysis were then used as the boundary conditions for the second step of the thermal stress analysis - the ANSYS analysis. Selected bond coat and ceramic material properties used in the stress and heat transfer analysis are shown below.

<u>Material</u>	<u>°F</u>	<u>K</u>	<u>Cp</u>	<u>E</u>	<u><math>\alpha</math></u>
		(BTU/ Hr Ft °F)	(BTU/ Lb °F)	(PSI)	(In/In/°F)
NiCrAlY	1100	3.63	.166	$14.5 \times 10^6$	$7.4 \times 10^{-6}$
NiCrAlY	2000	5.0	.171	2.0	9.2
ZrO <sub>2</sub> -8Y <sub>2</sub> O <sub>3</sub>	1100	.765	.158	4.2	5.6
ZrO <sub>2</sub> -8Y <sub>2</sub> O <sub>3</sub>	2000	1.08	.157	2.9	6.8

The second part of the thermal stress analysis consisted of a detailed multilayered 3-D isotropic brick ANSYS analysis. This 3-D finite element model is shown in Figures 2-6 and 2-7. The bond coat for the ceramic was modeled with one layer of brick elements, and the ceramic coating was modeled with three brick element layers. Due to symmetry, 30 degrees of the 60 degree arc was modeled. The strain values in the ceramic layers were generated for the eight time steps.

Shown in Figure 2-8 is a plot of the maximum strain and temperature in the ceramic layers during burst (transient accel), steady state maximum power and chop (transient decel). The highest tensile strains occur during the initial time intervals of the chop ( $t=205$  seconds). At this time a major portion of the ceramic layers has strains exceeding the fracture strain of the ceramic.

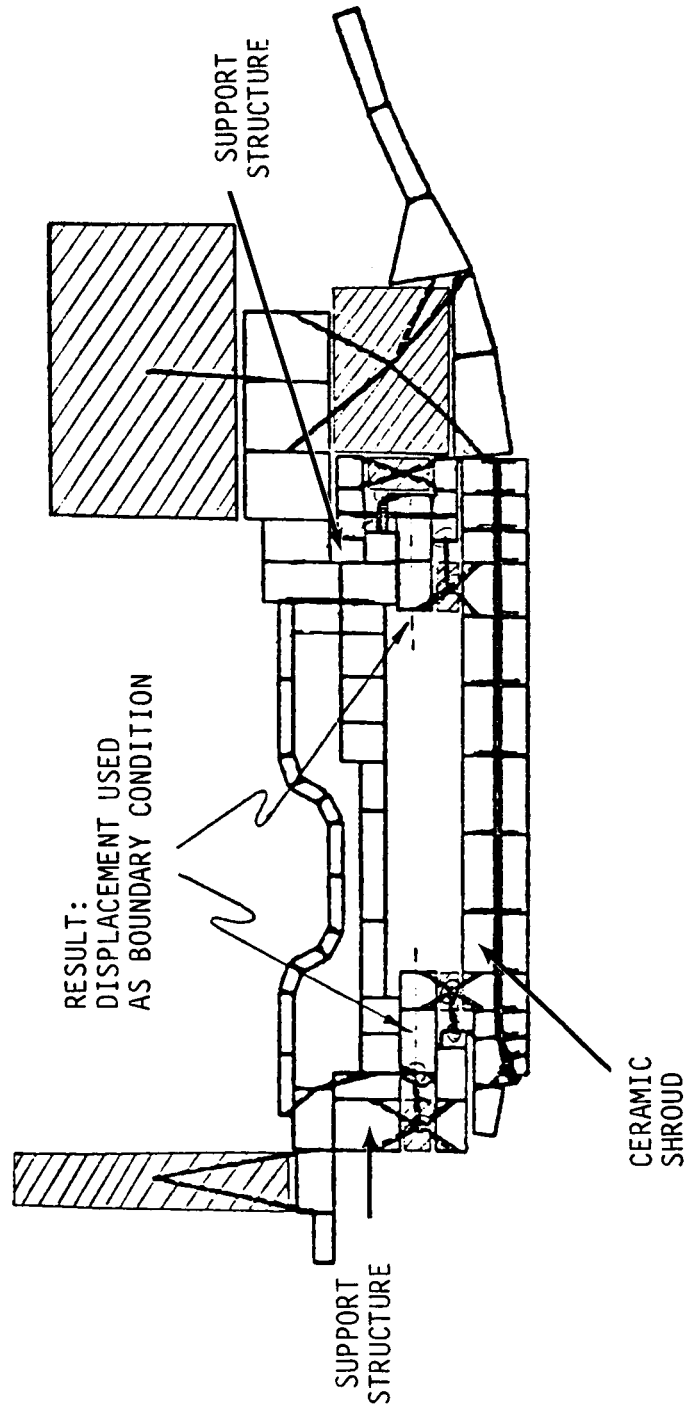


Figure 2-5. 2-D Finite Element Model.

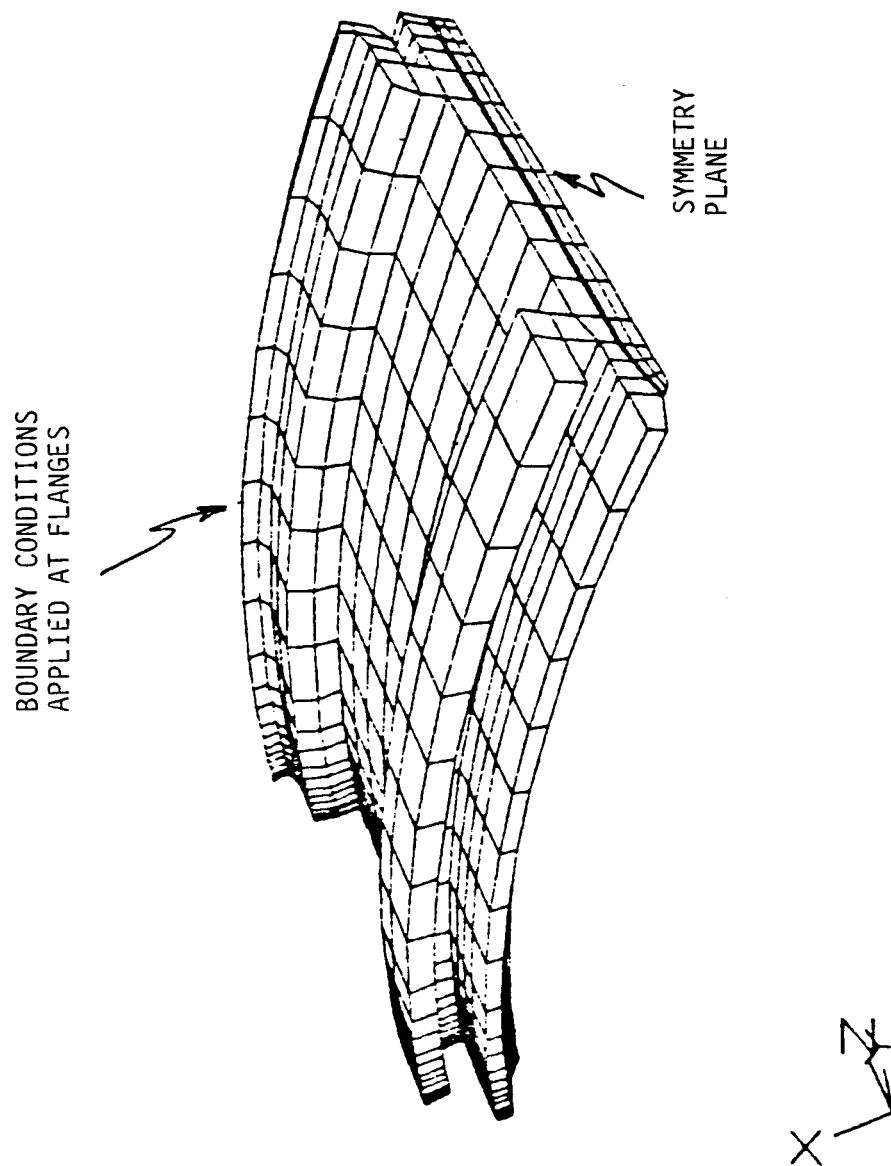


Figure 2-6. 3-D Isotropic Brick ANSYS Model.

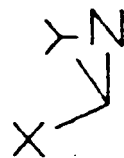
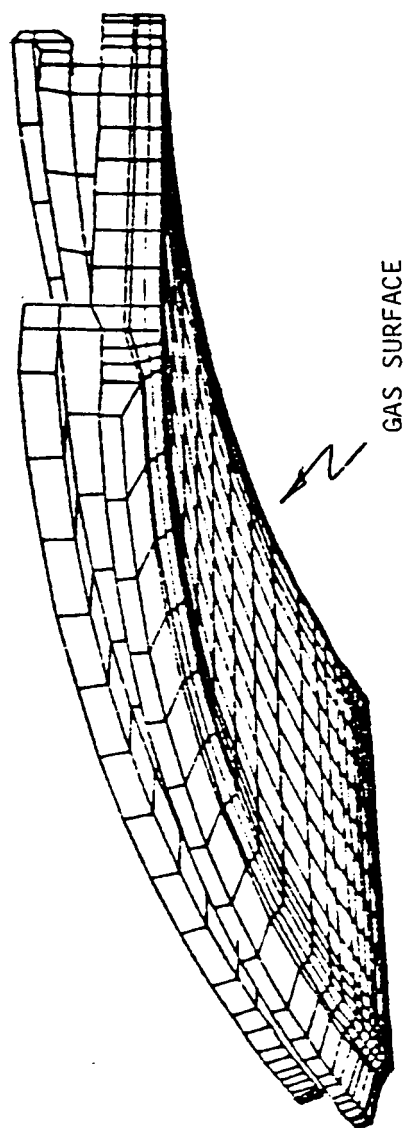


Figure 2-7. ANSYS Model.

$\epsilon_{\text{Hoop Max}} = .426\%$   
 @Temperature = 1312°F  
 $\epsilon_{\text{Axial}} = .19\%$   
 At Same Location

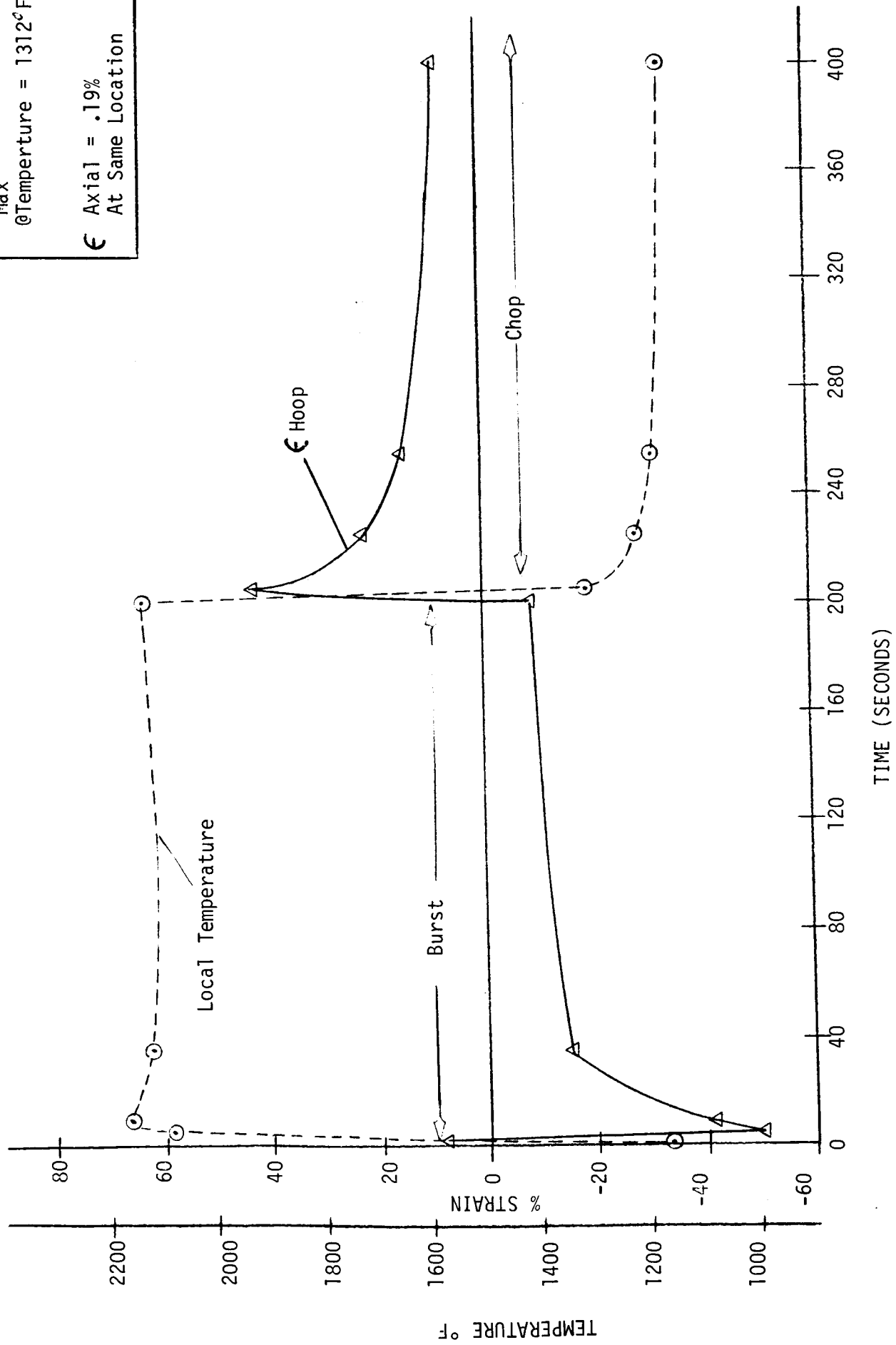


Figure 2-8. Maximum Transient Strain.

Shown in Figures 2-9 and 2-10 are the stress contours of the hoop and axial strains at  $t=205$  seconds. The strains are uniformly high over the entire ceramic shroud surface layer. The highest hoop strains occurred at the ceramic gas surface at the symmetry edge or center of the shroud. The critical location for the axial strains appears closer to the free edge.

### Conclusions of Thermal Stress Analysis

The thermal stress analysis of the ceramic shroud predicts the failure of the ceramic layer due to exceeding the fracture strain limit of the ceramic material. Failure of the ceramic coating does not occur during engine or component testing as predicted by this analysis. Limited cracking of the ceramic coating does occur during thermal shock testing (see Section 3.1.2) and engine testing (see Section 4.0). This cracking rarely leads to ceramic spalling/failure, and when spalling does occur it is very limited. The ceramic cracking which occurs during thermal shock testing and engine testing generally occurs at the ceramic/bond coat interface line in the GE coated shrouds, which was not predicted by this thermal stress analysis. Cracking generally occurs over the entire surface (mudflat cracking) of the Union Carbide shrouds and also at the ceramic/bond coat interface line. The cracks which occur on the surface of the Union Carbide coated shrouds are very fine and shallow and have not led to any ceramic spallation. It seems evident that even when the ceramic fracture strain is exceeded in the actual shroud the cracking is limited and does not have a major impact on the overall integrity of the ceramic coating (limited spallation).

There are a variety of reasons why the thermal stress analysis did not more accurately predict the integrity of the ceramic coating as given below:

1. The mechanical properties of the ceramic coating are not well understood and are highly dependent on the technique of the ceramic coating application. This is clearly evident as shown by the differences between the GE ceramic shrouds and the Union Carbide ceramic shrouds. These shrouds are similar in ceramic chemical composition but display very different characteristics during testing.
2. Initial cracking of the ceramic coating stress relieves the ceramic coating so that further cracking does not occur.



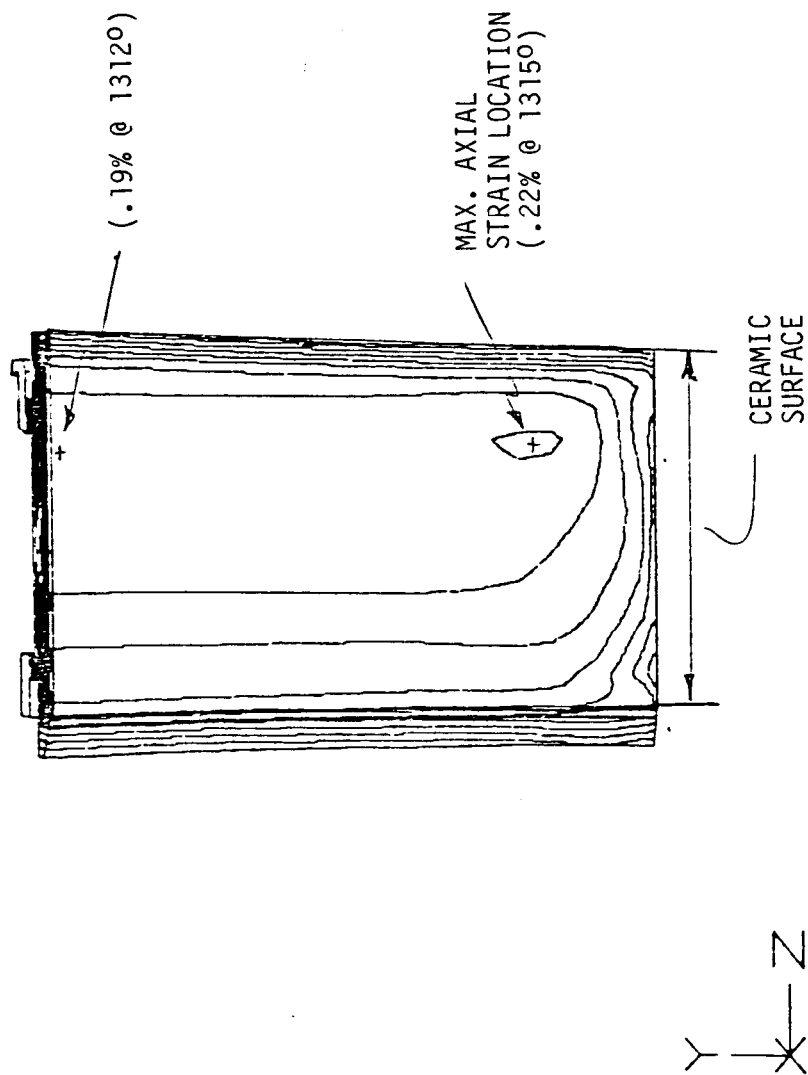


Figure 2-9. Ceramic Surface Stress Contours (Axial).

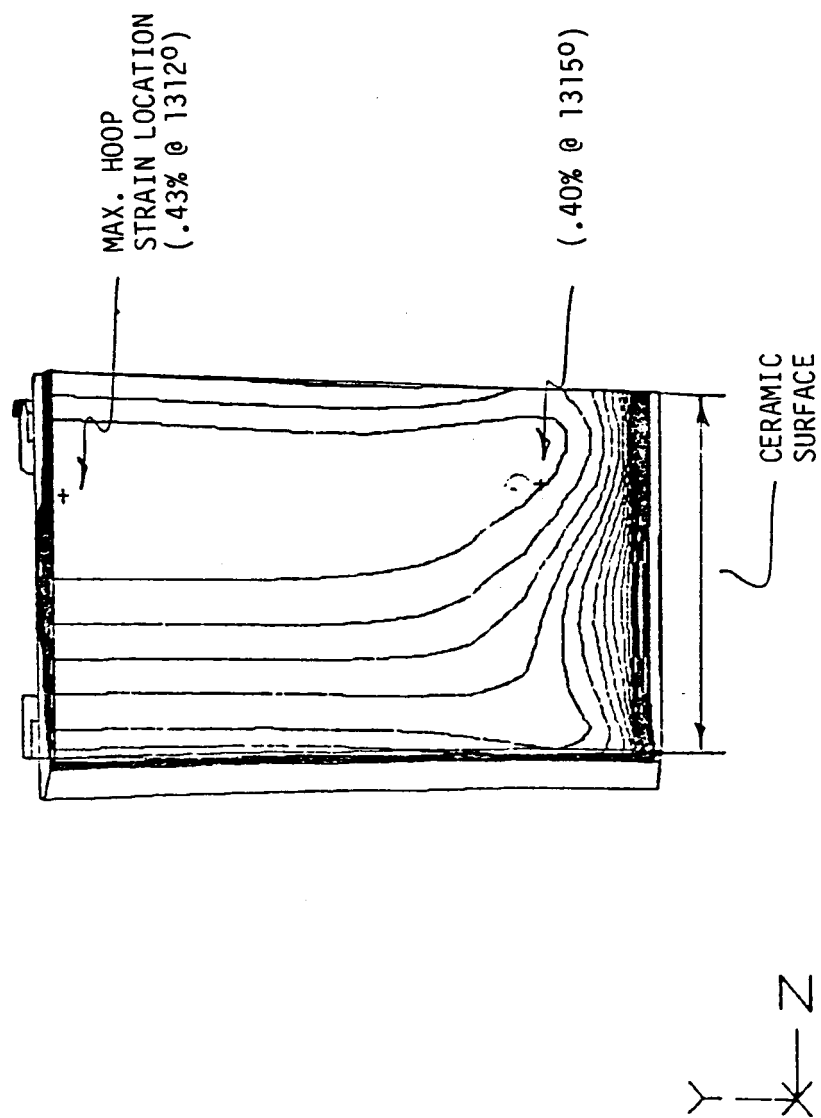


Figure 2-10. Ceramic Surface Stress Contours (Hoop).

3. The thermal transient temperature gradients in the ceramic coating are complex and not well understood. A more detailed transient heat transfer analysis would lead to a better understanding of the transient thermal stresses.

#### 2.1.2 Detail Drawings

The shroud casting detail production drawing was developed. The casting drawing and part number are common for all ceramic coating systems tested in this program. This casting drawing is also common with the solid type stage I shroud.

The initial ceramic shroud machining drawing was also completed. This drawing is common for all the ceramic coating systems tested with this program. Separate part numbers specify the different coating processes by drawing notes.

The initial ceramic shroud drawing was updated throughout the program to reflect the latest processes and requirements. The final production ceramic shroud drawing was issued during Phase III.

#### 2.1.3 Material Specifications

Preliminary material specifications were issued under this phase of the program. These preliminary specifications were used to manufacture the initial ceramic shroud specimens for component testing. Where possible previously issued off-the-shelf specifications were used for the bond coat powder and ceramic powder. These specifications were updated throughout the program until the final specifications were issued during Phase III for the production drawing. See Appendix A for definition of all the final production ceramic shroud specifications.

#### 2.1.4 Quality Assurance Criteria

Preliminary quality assurance criteria were established under this phase of the program to assure the integrity of the ceramic and bond coatings. Critical post-spray dimensional, hardness, and density requirements were established.

Nondestructive testing methods, including infrared thermographic and eddy current techniques, were tested to determine the integrity of the ceramic and bond coating after the coating process and after all machining. These nondestructive evaluation techniques yielded inconclusive defect detection due primarily to the surface layer variations. The quality of production ceramic shrouds is controlled like all previous shroud systems by careful manufacturing process control. See Appendix B for definition of production quality assurance procedures.

Coupon thermal shock Jets tests were performed to determine ceramic and bond coat integrity. These test coupons (1" diameter buttons) were subjected to thermal stresses similar to what happens to a shroud in an engine. Shown in Figure 2-11 are the ceramic coupons during thermal shock testing. Eight coupons can be tested at the same time. The ceramic coupons are cycled in and out of the flame while the back end of the coupon is cooled with a jet of air. The flame and the cooling air are adjusted so that required temperatures are achieved as determined by thermocouples. These test coupons are an economical method to evaluate various parameters, processes, and compositions which affect the integrity of ceramic shrouds. Numerous coupon thermal shock tests were performed with the following variations:

1. All three types of ceramic coating systems were tested: GE VPD, GE APS and Union Carbide SAP.
2. Variations in ceramic application techniques were tested.
3. Variations in ceramic coating and bond coating thicknesses were tested.
4. The thermal gradient across the ceramic was varied.

These tests were concluded in Phase II of the program and helped to determine the best coating process, material, and temperature capability of the ceramic shrouds. Shown in Table 2-1 are the results of the thermal shock tests performed on the three coating systems. The ceramic bond coating thickness was 10 mils for all coupons tested which is the same as the engine tested ceramic shrouds. These results clearly show that the GE VPD system is not as durable as the GE APS system or the Union Carbide SAP system. These results were confirmed by engine testing (see Section 4.1 Engine Testing) which led to the GE VPD system being dropped from the program. The poor performance of the

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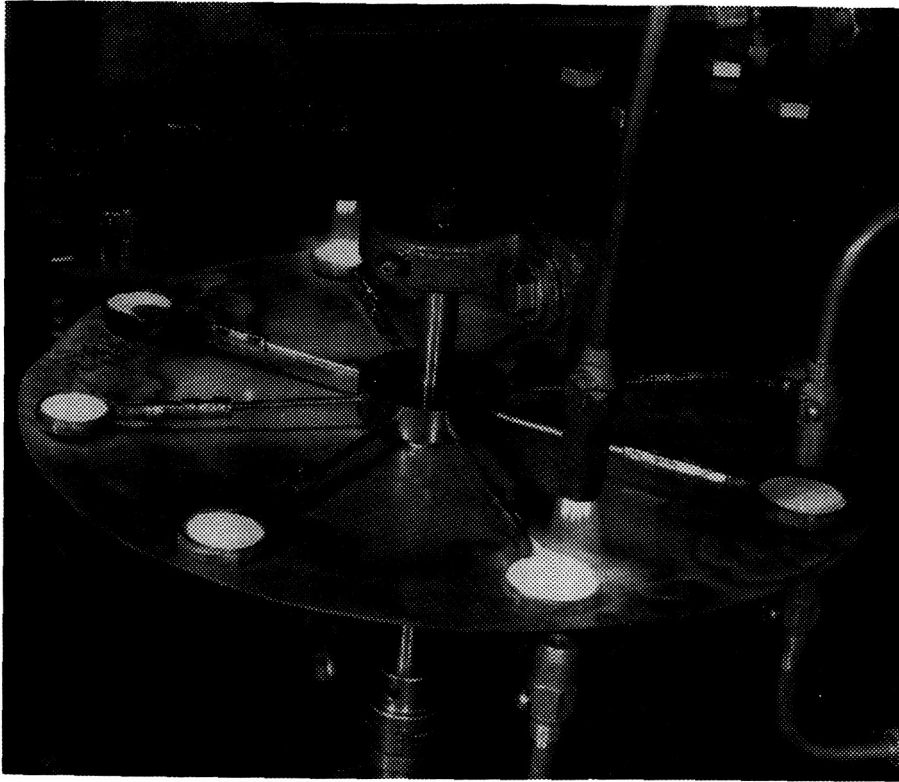


Figure 2-11. Ceramic Coupon Thermal Shock Test (Jets).

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GE-VPD system is partly attributed to the use of composite  $ZrO_2-8Y_2O_3$  plasma spray powder, which results in a ceramic coating which is not fully chemically homogeneous. The results in Table 2-1 also clearly show that thicker ceramic coatings are less durable. The maximum coating thickness allowed is about 48 mils in the engine. Shown in Figure 2-12 are examples of the type of cracks which occur in the buttons during testing. Again, these results agree with the engine test results. Because of the success of this testing method and relatively low cost, each coating lot of production ceramic shrouds will be coupon thermal shock tested to assure the integrity of the coating as defined by GE Specification F50TF60.

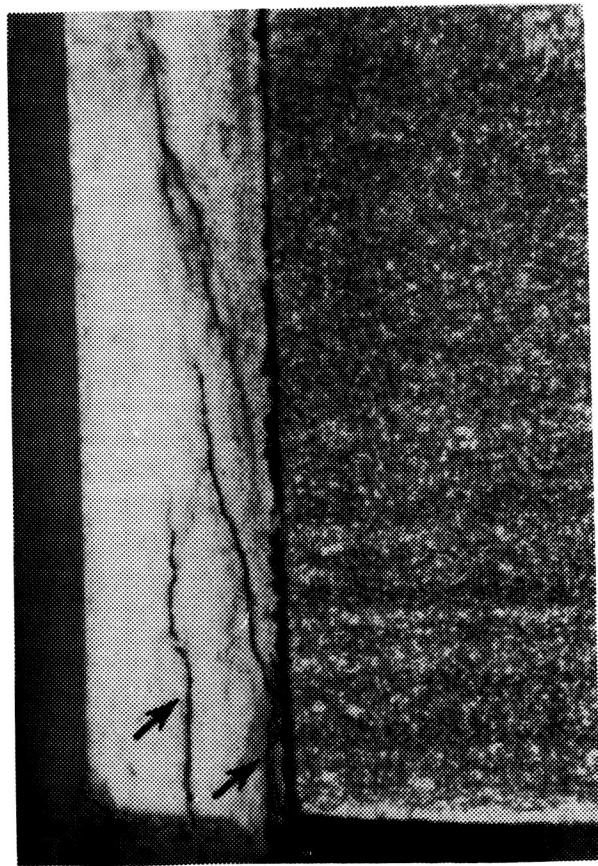
TABLE 2-1. Thermal Shock Jets Test Results At 2200°F (Coupons).

<u>Vendor</u>	<u>System</u>	<u>Ceramic Thickness (mils)</u>	<u>No. Cycles*</u>	<u>% Bond Line Cracking</u>
(GE-MTL)	VPD	50.9	2000	100 (spall)
		45.9	2000	91
		45.5	2000	100
		45.0	2000	80
(GE-MTL)	APS	53.5	2000	83
		44.4	2000	35
		44.3	2000	6
		44.0	2000	14
(Union Carbide)	SAP	62.8	2000	100
		44.9	2000	10
		45.0	2000	8

\*Cycles are 20 second duration of heating the ceramic surface to 2200°F (backing approximately 1550°F) and cooling the ceramic surface to below 800°F.

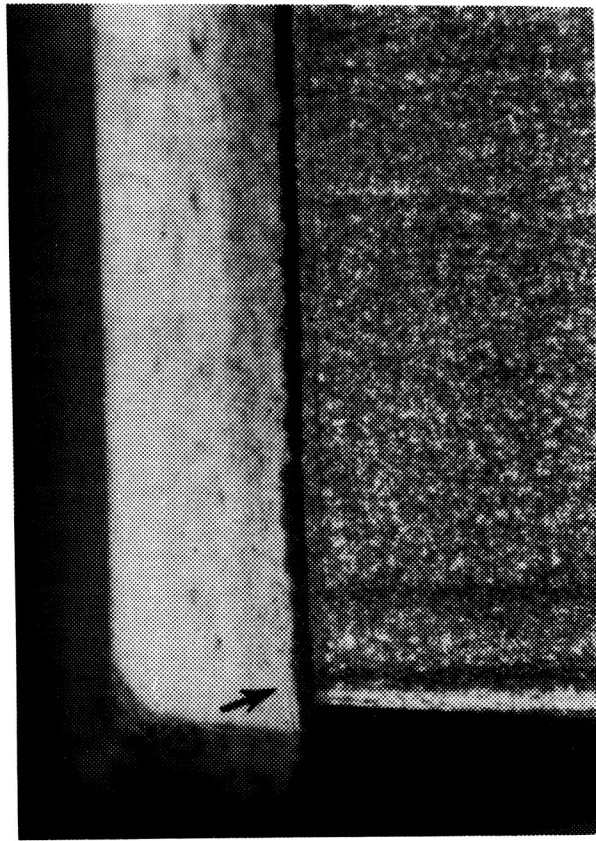
#### 2.1.5 Manufacturing Cost Estimates

Preliminary manufacturing cost estimates of the ceramic shroud were made under this early phase of the program. These cost estimates showed the ceramic shroud as being a cost reduction over the current production shroud. Final preproduction costs completed in Phase III of the program also show the ceramic shroud as being a cost reduction (see Section 1.1 Program Summary).



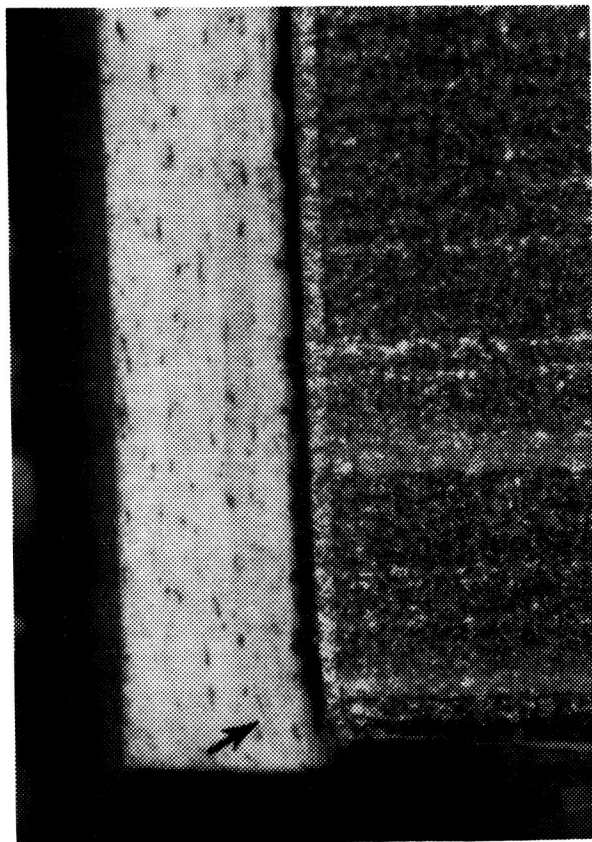
GE-MTL VPD

20X



GE-MTL APS

20X



UC SAP

20X

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Figure 2-12. Examples Of Bond Line Cracks.

## 2.2 TASK II - MANUFACTURING FACILITY SETUP AND PROCESS DEVELOPMENT

### 2.2.1 Manufacturing Hardware

In this task, the fixturing hardware necessary to produce the modified ceramic shroud system was fabricated. The plasma spray facility was equipped with the appropriate hardware, including suitable controls necessary for computer controlled multiple part processing of the T700 ceramic shroud segments. Plasma spray parameters were established and the test coupons needed to verify these parameters were plasma sprayed. The final manufacturing technical plan was completed in Phase III of this program and is shown in Appendix B.

### 2.2.2 Manufacturing Process Specification

Preliminary manufacturing process specifications were described under this phase of the program to manufacture the T700 HPT ceramic shrouds. These preliminary specifications described in detail the processes to manufacture shrouds in Phase II. One of the major decisions made during this phase of the program was to apply the bond coating and ceramic coating after all machining of the backing. Applying the ceramic coating after machining reduces the mechanical fixturing stresses on the ceramic and reduces the ceramic exposure to machining oil. The only machining done on the ceramic shrouds after the coating is applied is to finish grind ends of the shrouds, EDM the end spline seal slots, and grind the flowpath.

Under Phase III of this program, the final manufacturing technical plan was issued which defines in detail the ceramic shroud manufacturing process shown in Appendix B.

### 2.2.3 Coating Property Evaluations

Property measurements were conducted on test coupons which represented the planned production ceramic shroud. These test coupons were used to evaluate the various ceramic and bond coating application techniques and materials. The properties measured were elasticity, tensile strength, thermal conductivity, particle size, thermal expansion and the ceramic and bond coat



maximum temperature capabilities. Coating process iterations were conducted to yield the optimum metallurgical properties. These material properties were used in the thermal and stress analysis described in Section 2.1.1.

### 3.0 PHASE II - FULL SCALE HARDWARE FABRICATION

#### 3.1 TASK III - FABRICATE AND VERIFY FULL SCALE COMPONENTS

##### 3.1.1 Fabricate Shrouds

Initial sets of shrouds were ordered under Phase II of this program for engine testing in Phase III. At this time in the program all three types of ceramic coatings were still under contention for final production application. Twenty finished shrouds were made to the processes and quantities described below:

1. Six segments were produced using the Vacuum Plasma Deposition NiCrAlY bond coat and composite  $ZrO_2-8Y_2O_3$  powder process and equipment defined in Phase I.
2. Eight segments were produced using the Air Plasma Spray NiCrAlY bond coat and the sintered  $ZrO_2-8Y_2O_3$  powder, heat treated top coat process.
3. Six segments were produced using the Shielded Arc Plasma CoNiCrAlY bond coat and the fused  $ZrO_2-7Y_2O_3$  powder, heat treated top coat process.

##### 3.1.2 Verify Components

Cyclic thermal shock tests were conducted on full scale ceramic shrouds and a current production Bradelloy shroud for comparison. The testing included the three candidate ceramic shroud coating systems: GE APS, GE VPD and Union Carbide SAP. The thermal shock testing was accomplished in such a way as to approximate the maximum temperatures, the radial thermal gradients through the ceramic, and the transient temperatures that occur in a T700 engine.

For the thermal shock testing of the ceramic shrouds, special fixtures were designed and built which secure and cool the shrouds so that they approximate the conditions in a T700 engine. Shown in Figures 3-1 through 3-4 are the fixture designs for the thermal shock testing. The shroud temperatures are controlled by the level of cooling air used and the heat input to the ceramic surface exposed to the flame tunnel. The cooling level needed to achieve proper shroud temperatures and gradients can be regulated for each individual shroud. Verification of transient and steady state shroud temperatures was

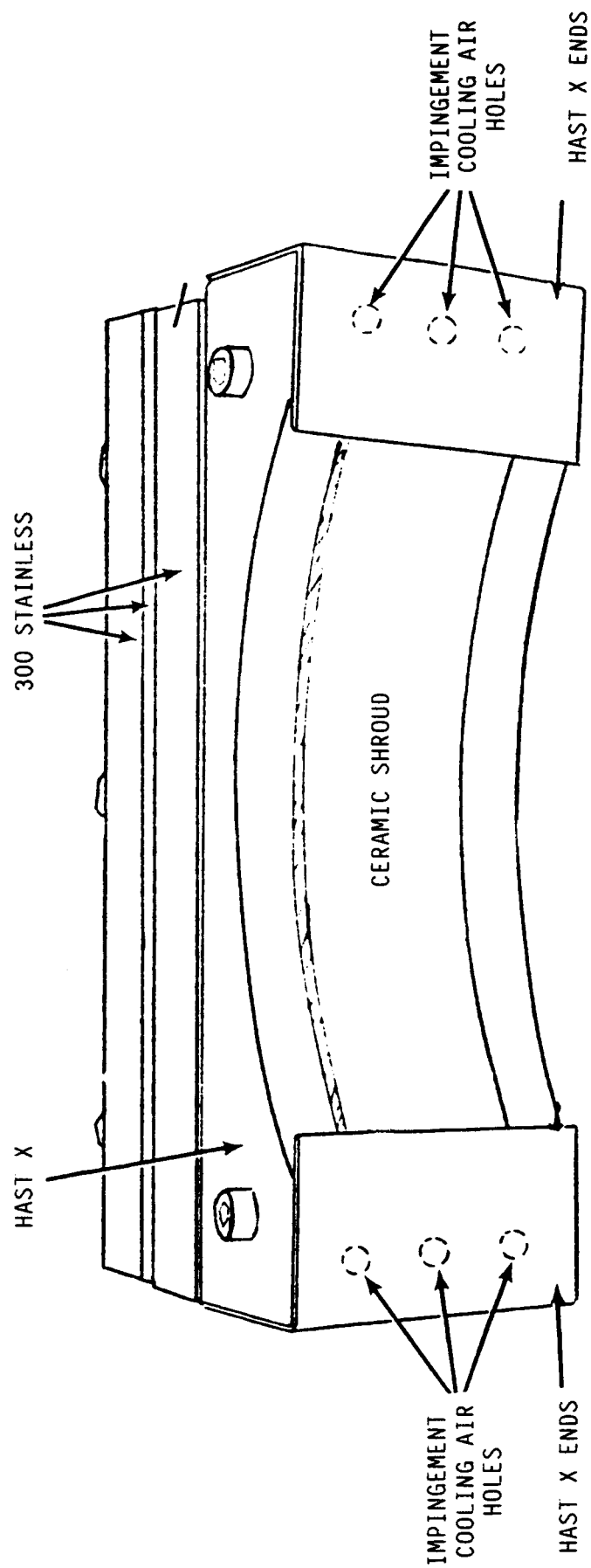


Figure 3-1. Thermal Shock Test Shroud and Shroud Holder.

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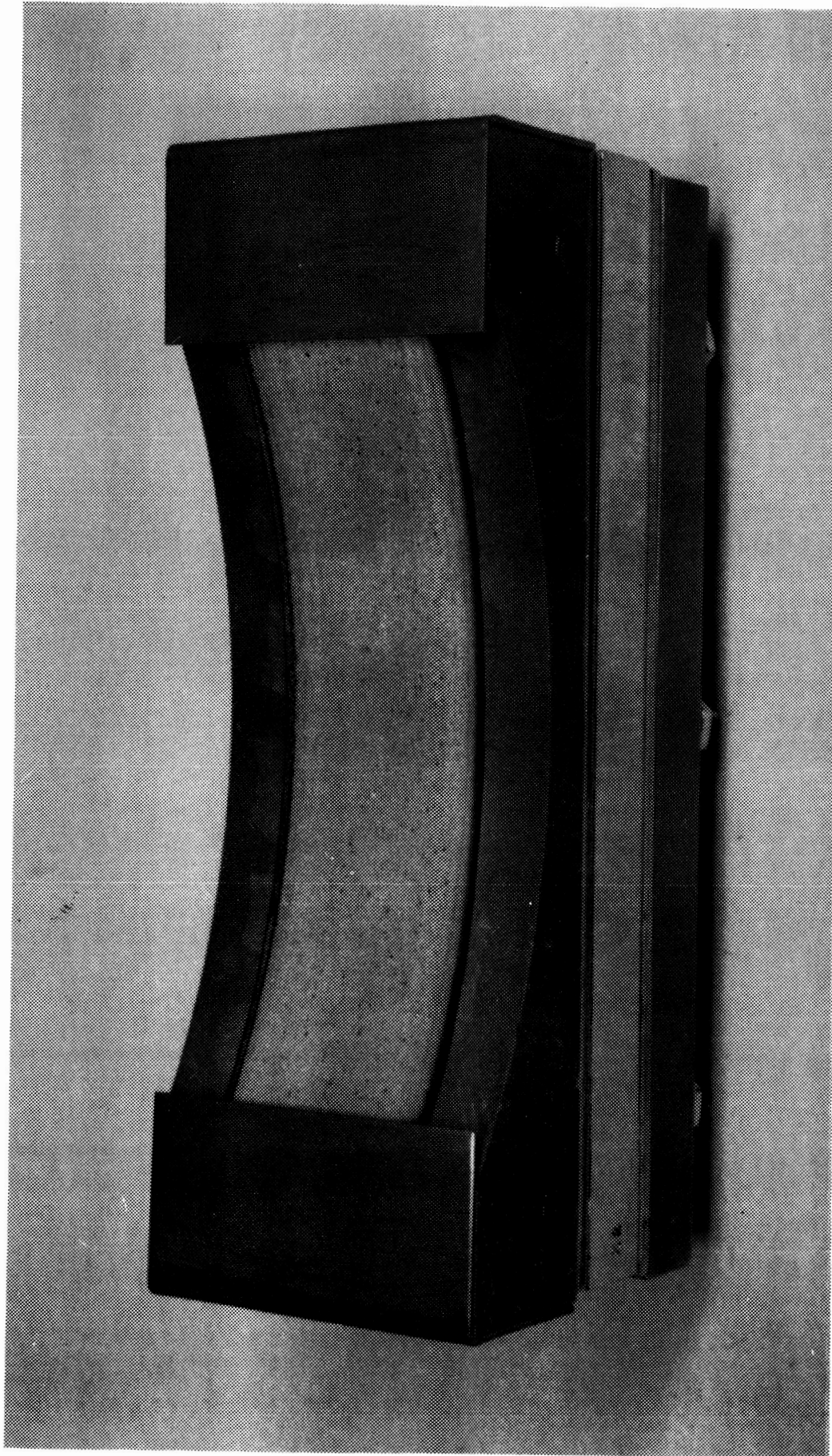


Figure 3-2. Ceramic Shroud in Thermal Shock Fixture Pretest.

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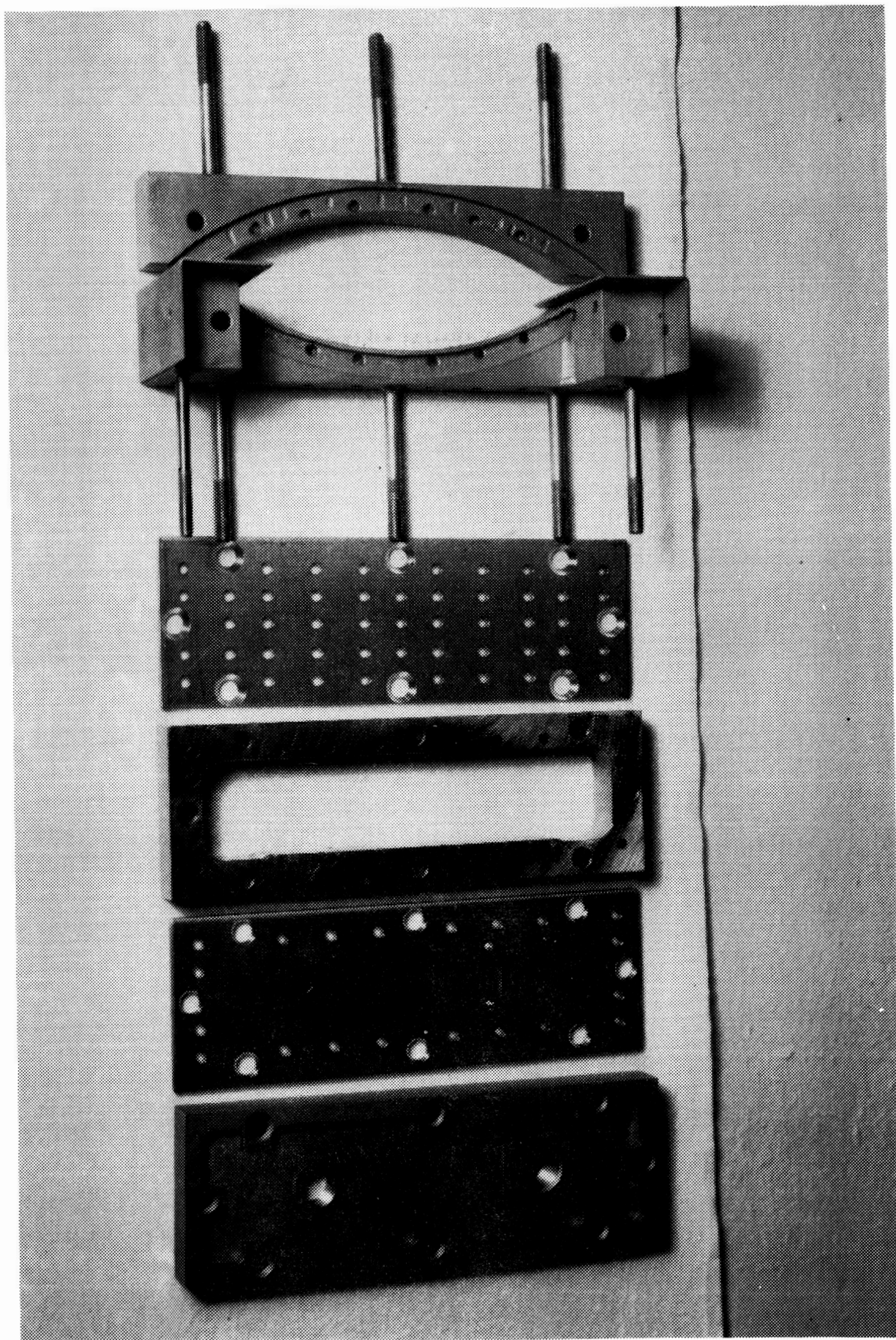


Figure 3-3. Thermal Shock Fixture Disassembled.



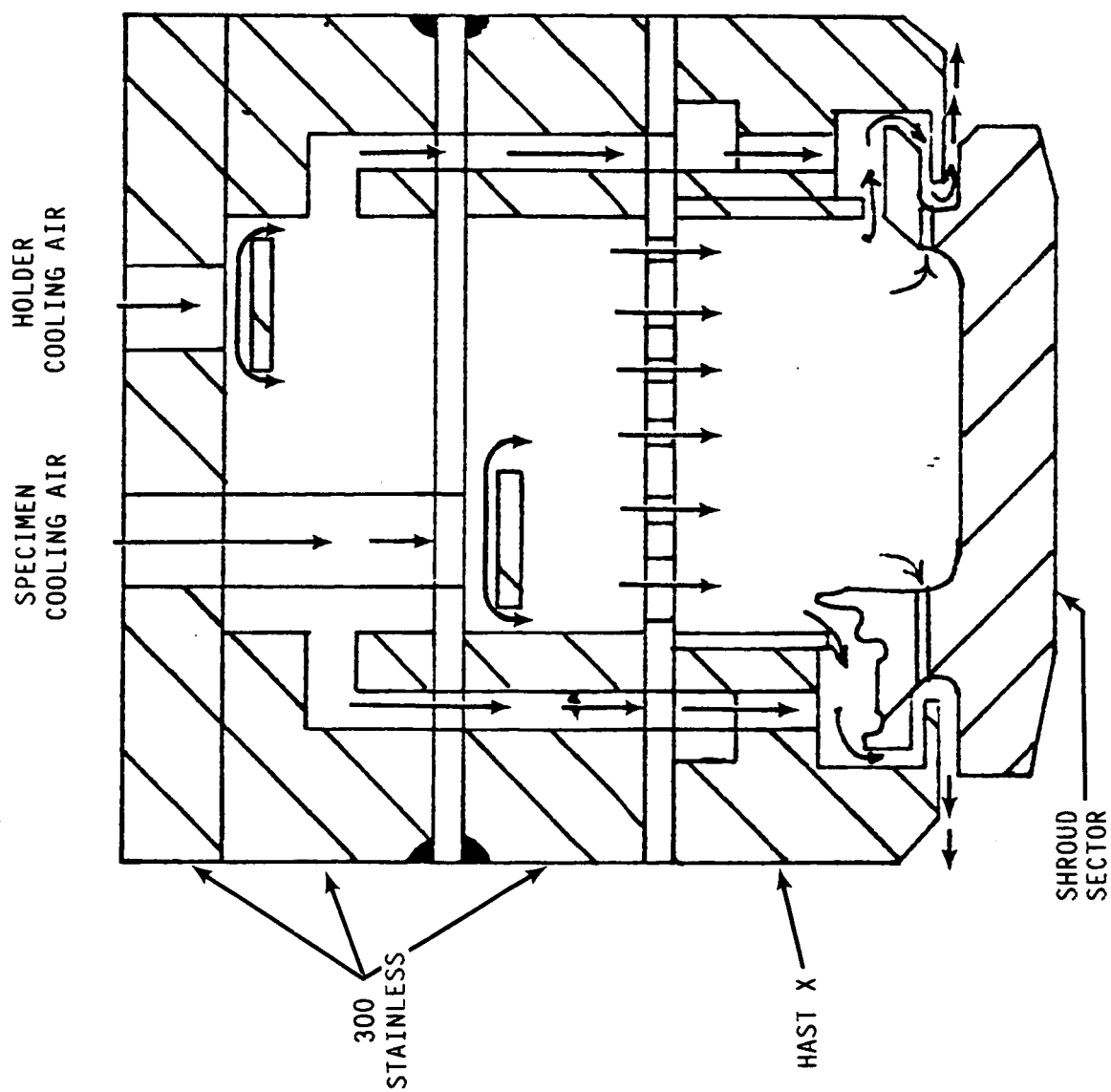


Figure 3-4. Thermal Shock Test System.

achieved by thermocouples attached to the backing of the ceramic shroud. The temperature of the shroud surface was determined by an optical pyrometer. Two shrouds were thermal shock tested concurrently. Figure 3-5 depicts the thermal shock facility during testing. Figure 3-6 shows the ceramic shrouds during cyclic thermal shock testing.

The following cyclic thermal shock tests were performed on the four shroud specimens:

1. One Thousand thermal cycles at anticipated engine conditions to verify the integrity of the ceramic coatings. If less than 50% of the ceramic bond or top was cracked along the perimeter of the ceramic shroud, the test was deemed a success.
2. After completion of the 1000 thermal cycles an additional 370 abusive thermal cycles with increasing radial gradients were run to assess the maximum capability of the ceramic shrouds.

The three ceramic shrouds were thermally cycled between conditions corresponding to the T700-401's  $T_{4.1}=2358^{\circ}\text{F}$  gas temperature and approximately ambient temperature. This approximates the most severe engine thermal cycle possible (from start of engine to maximum temperature back to engine shutdown) for 1000 cycles. Shown in Figure 3-7 are the transient temperatures of a ceramic shroud and a new Bradelloy shroud for the first 1000 thermal cycles. For the 1000 thermal cycles the ceramic shrouds were tested to the following conditions:

- Maximum ceramic top coat temperature =  $2230^{\circ}\text{F}$
- Maximum bond coat temperature (calculated) =  $1900^{\circ}\text{F}$
- Maximum backing metal temperature =  $1540^{\circ}\text{F}$
- Maximum steady state temperature gradient across the shroud thickness =  $690^{\circ}\text{F}$
- Maximum thermal gradient along the shroud circumferential length =  $100^{\circ}\text{F}$
- Each thermal cycle equals 3 minutes in the hot station and 3 minutes in the cool-down station, for a total of 6 minutes per cycle.

The above temperature conditions approximate the ceramic shroud temperature conditions in an engine with the current production shroud cooling flow

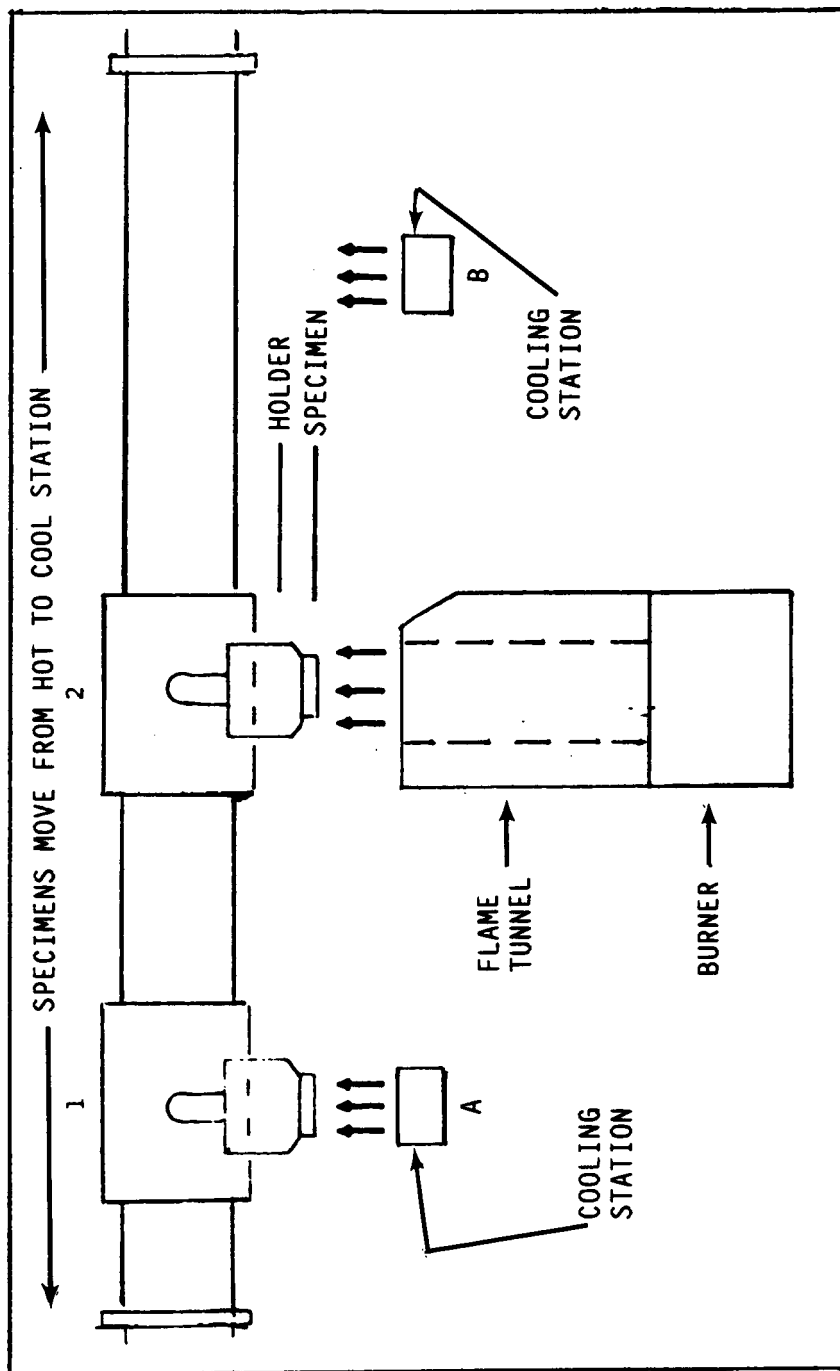


Figure 3-5. Thomson Laboratory Thermal Shock Tester Schematic.



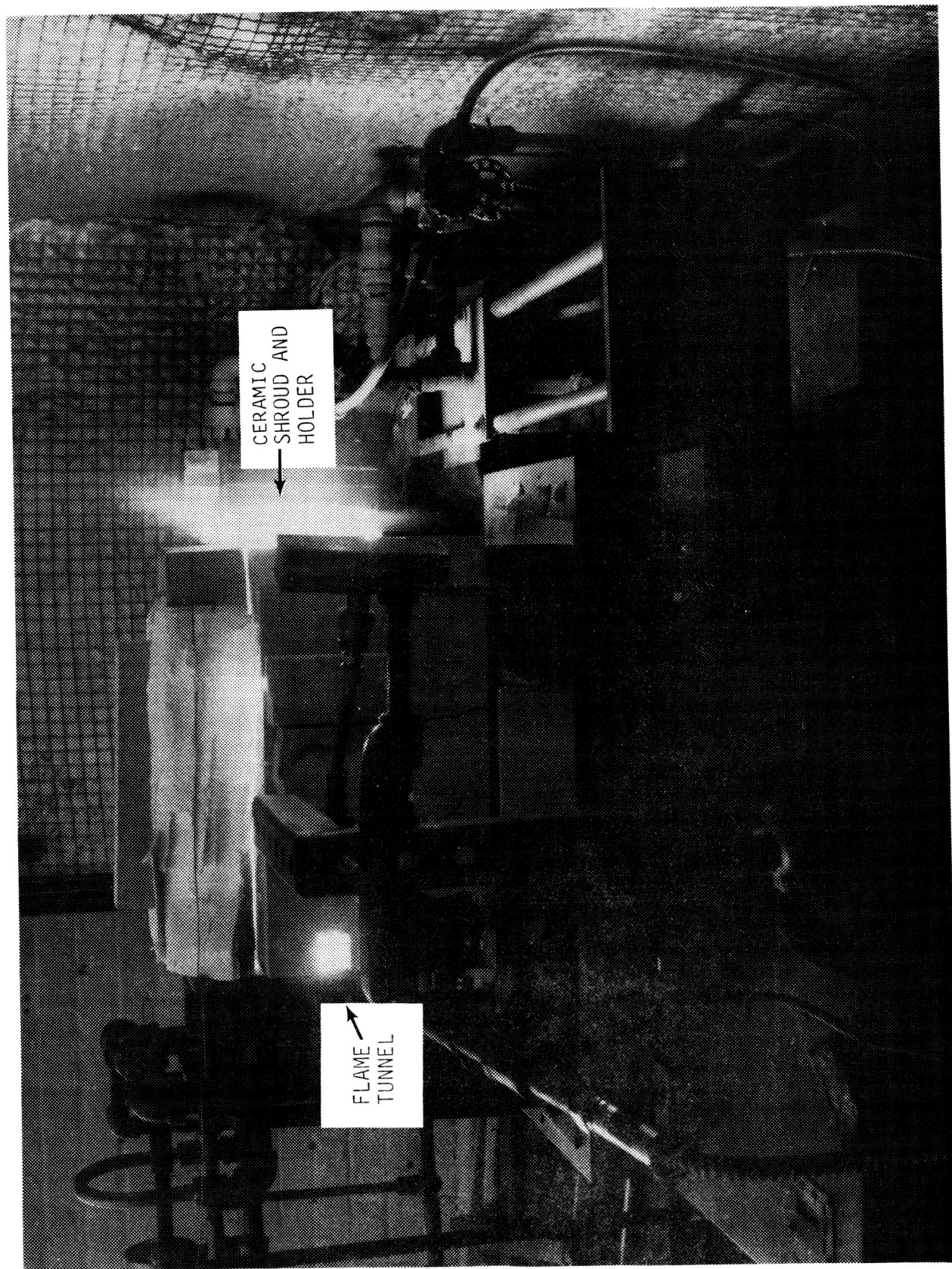


Figure 3-6. Ceramic Shrouds During Thermal Shock Testing.

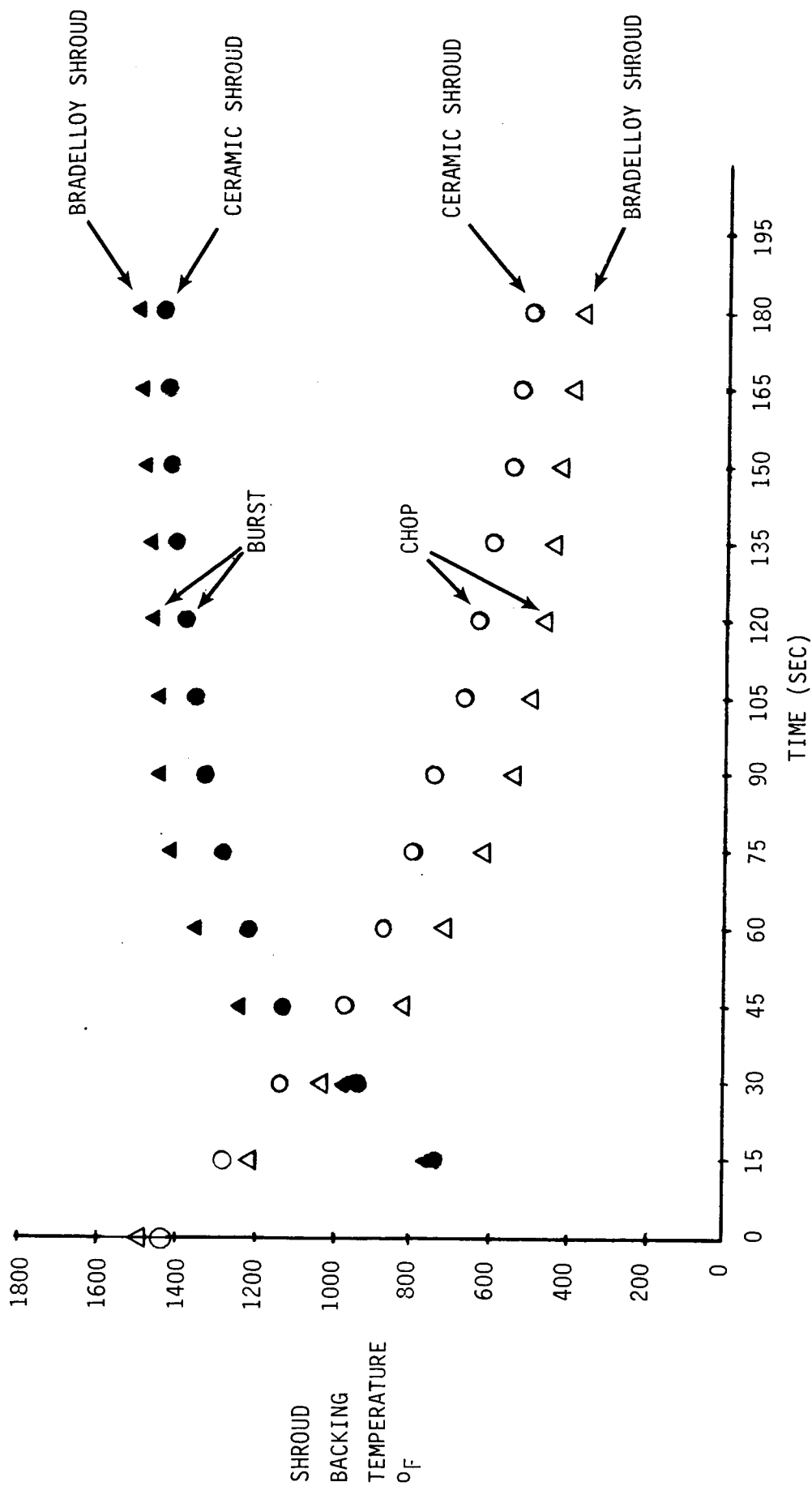


Figure 3-7. Thermal Shock Test - Shroud Backing Temperature vs Time.

.872% Wc. This temperature condition is more severe (higher radial temperature gradient) than the temperature conditions with .699% Wc (the planned production cooling flow).

At the completion of the 1000 thermal cycles all three types of ceramic shrouds showed no loss of ceramic coating or cracking under 50X magnification. The reference Bradelloy shroud also showed no distress. The ceramic shrouds were then thermal shock tested for an additional 370 thermal cycles, increasing in severity both the maximum shroud surface temperature and the gradient across the shroud thickness as shown below:

<u>Ceramic Flowpath Surface Temperature</u>	<u>Backing Temperature</u>	<u>No. of Cycles</u>
2230	1540	20
2230	1490	50
2230	1440	50
2230	1390	50
2280	1540	50
2330	1540	50
2380	1490	50
2430	1440	50
	Total	370 Cycles

At the completion of all thermal shock testing the ceramic shrouds were extensively metallurgically examined to determine their integrity. Figure 3-8 depicts the location of the cracking which occurred in the ceramic from the additional thermal shock testing. No spallation of the ceramic occurred for any of the ceramic coatings. This type of cracking is similar to the type of cracking which occurs from engine testing (see Section 4.2). A summary of the type of cracking is outlined below:

- |          |     |   |
|----------|-----|---|
| (GE-MTL) | VPD | - Forward edge bond line cracking   |
|          |     | - Contamination in bond coat/substrate                                    |
|          |     | - Circumferential/axial cracking initiates in ceramic, close to bond coat |
| (GE-MTL) | APS | - Circumferential/axial cracking initiates in ceramic, close to bond coat |
|          |     | - T/E vertical cracking (wave pattern)                                    |

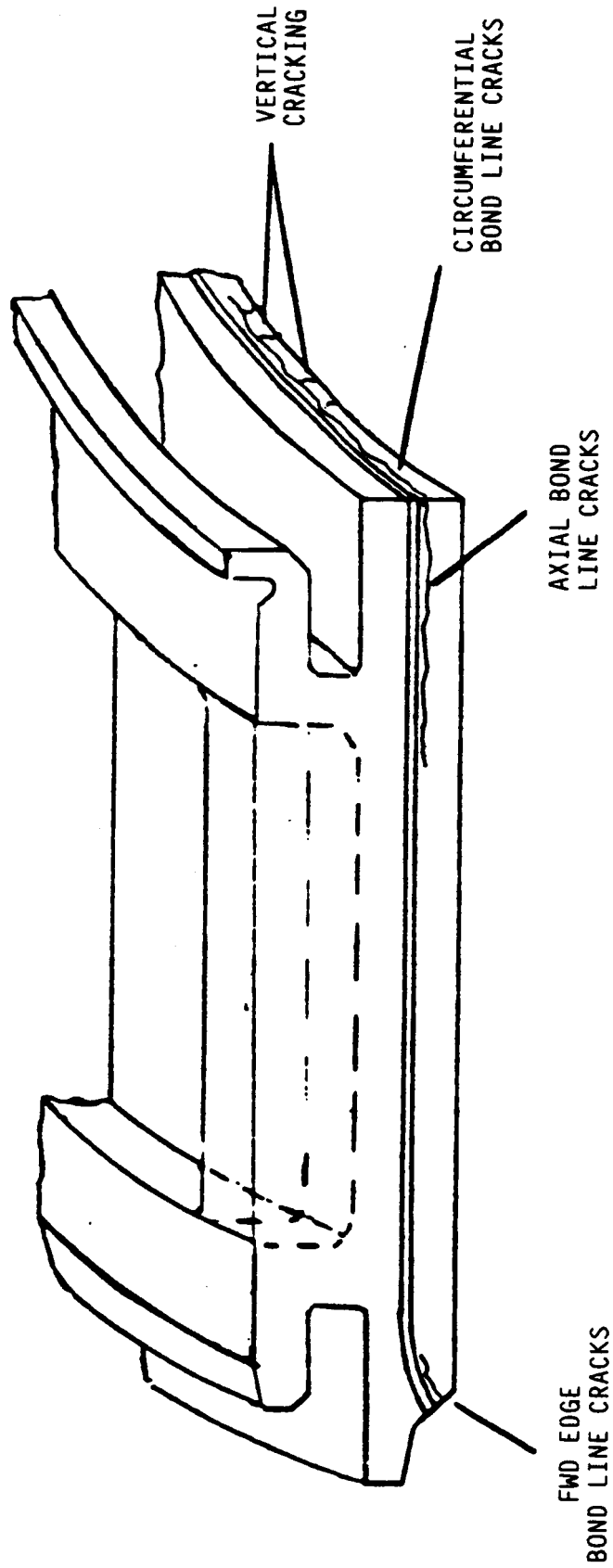


Figure 3-8. Additional Thermal Shock Test Results Showing Cracking Definition.

- |               |     |   |   |
|---------------|-----|---|---|
| Union Carbide | SAP | - | Circumferential/axial cracking initiated in ceramic and migrates along ceramic/ceramic* bond line |
|               |     | - | Extensive T/E vertical cracking   |

\*Internal ceramic/ceramic bond line is caused by heat treating cycle between ceramic layers.

The amount of bond line cracking is shown below:

- GE VPD
  - 15.2% of edge cracked
- GE APS
  - 29.9% of edge cracked
- Union Carbide SAP
  - 42.8% of edge cracked

The three types of ceramic shrouds were sectioned and the axial or circumferential depth (mils) of cracking was determined:

		<u>T/E (Right)</u>	<u>T/E (Center)</u>	<u>T/E (Left)</u>	<u>L/E (Center)</u>
(GE-MTL)	VPD	75	34	35	20
(GE-MTL)	APS	35	26	0	90
(Union Carbide)	SAP	70	67	315	0

### Conclusions

- No spalling of the ceramic coated shrouds occurred after completion of the standard 1000 cycles of thermal shock testing or after the additional abusive 370 thermal cycles.
- The type of cracks which occur in the ceramic coating are similar in type and location to engine test results (see Section 4.1).
- Contrary to engine and coupon thermal shock tests results, the GE VPD system had the least percentage of bond line cracking. The GE APS system had the least amount of T/E cracking which agrees with engine test results.

#### 4.0 PHASE III - PILOT PRODUCTION AND QUALIFICATION TESTING

##### 4.1 TASK IV - UPDATE SPECIFICATIONS AND COST ESTIMATES

Under this task of the program, the ceramic shroud material process specifications and cost estimates were updated so that production quality shrouds could be ordered under Phase III of the program for qualification. The updated cost analysis indicated that the GE APS system was the lowest cost system because bond and ceramic coatings are applied in air rather than in a vacuum, as required for the GE VPD ceramic system. The GE APS system also costs less than the UC SAP system because of the added complexity of the UC SAP system.

##### 4.2 TASK V - ENGINE TESTING

Extensive engine testing of ceramic shrouds was performed to thoroughly evaluate the integrity and benefits of ceramic shrouds. A total of four endurance and LCF engine tests were conducted. The standard T700 endurance and LCF cycles are shown in Figures 4-1 and 4-2. Each engine test evaluated six ceramic shrouds. Three different ceramic shroud systems have been evaluated in these engine tests. In addition, a sand erosion test was completed which evaluated erosion resistance of ceramic compared to current production shrouds. An overview of the major variations between engine tests is presented in Table 4-1.

The overall results of these engine tests are excellent and culminated in production qualification of ceramic shrouds for the T700 engine. The qualified shroud system meets GE Specification F50TF60 and consists of air plasma sprayed NiCrAlY bond coat and air plasma sprayed  $ZrO_2-8Y_2O_3$  (8YSZ) top coat using sintered zirconia. Two ceramic shroud systems performed adequately in engine tests, but the final choice of a system for qualification was based on post-test microstructural inspections which showed less internal cracking. Coating cracks occur in most of the engine-tested shrouds; however, much of the coating spallation appears to occur during engine disassembly. In

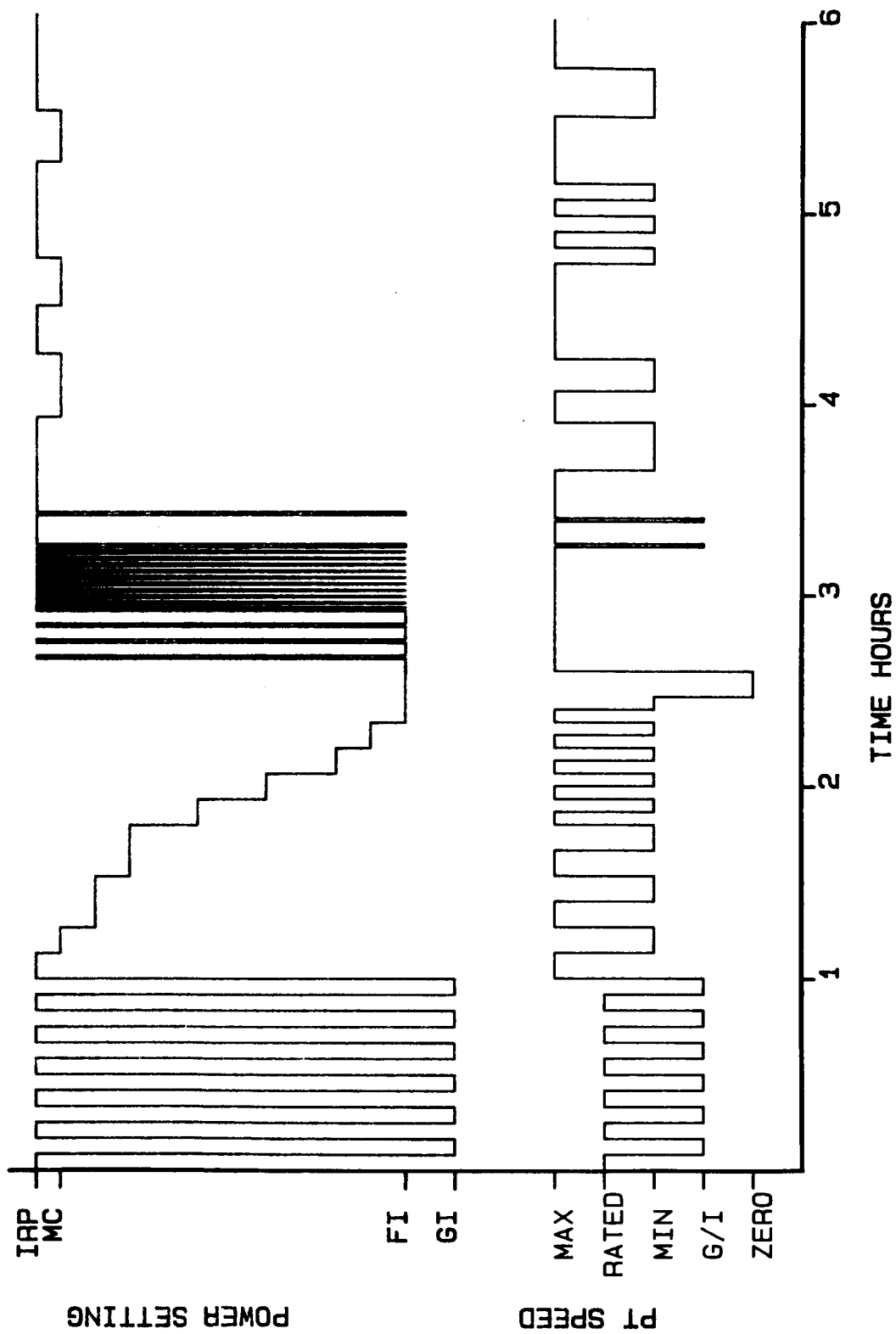


Figure 4-1. Standard T700 Low Cycle Fatigue (LCF) Cycle.

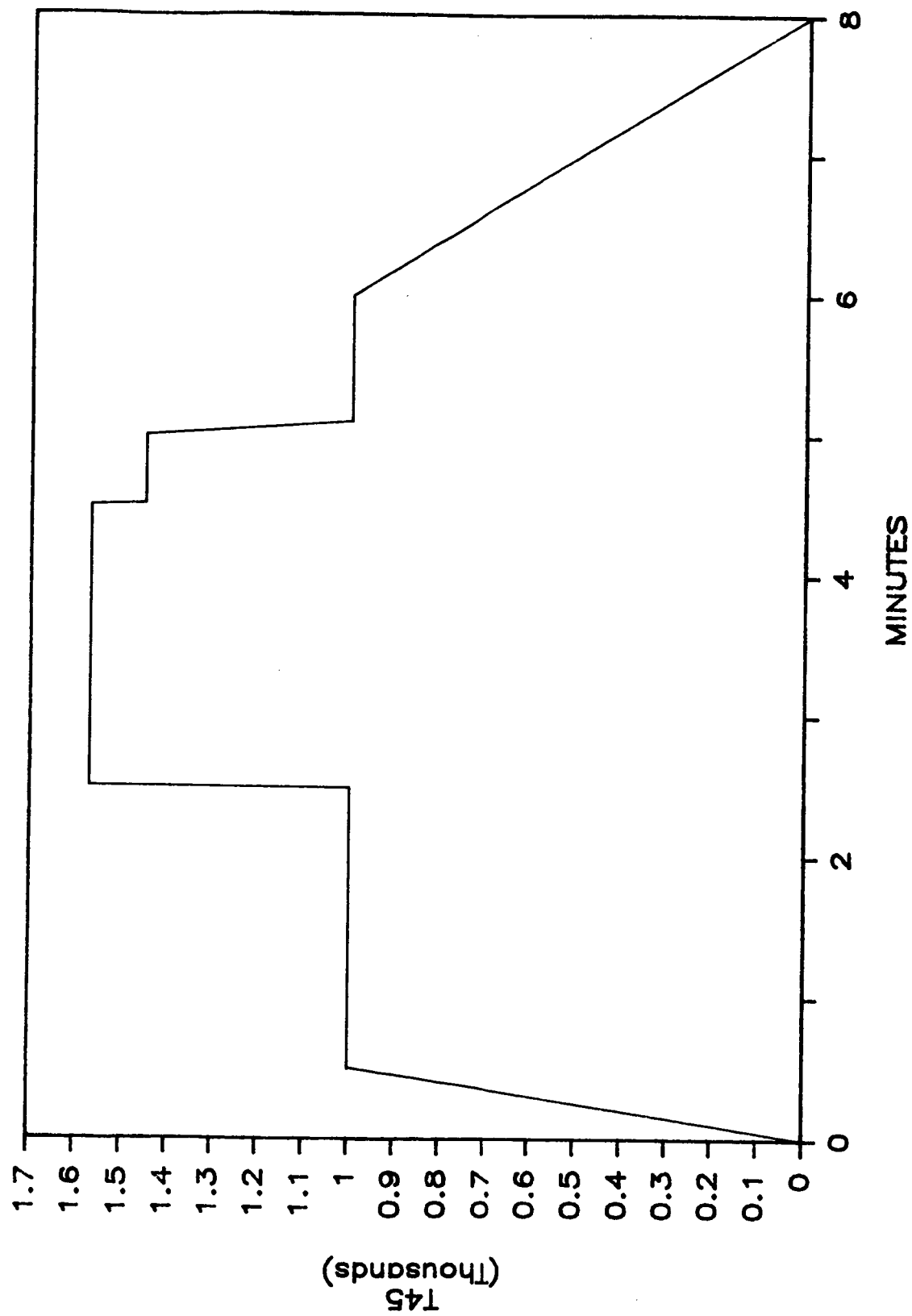


Figure 4-2. Standard T700 Endurance Cycle.



TABLE 4-1. Synopsis of T700 Engine Testing of Ceramic Shrouds.

Engine	Type of Test	Shroud Cooling Flow	Shroud Systems	Significant Event	Maximum Turbine Inlet Temperature (T4-1)
374117-2	3300 LCF Cycles plus Stall Test	Reduced 20%	2-GE APS 2-GE VPD 2-UC SAP	Burnt off Stage 1 Blade Tips	2333°F
212108-4	360-Hour Endurance plus 140 Hours	Standard	3-GE APS 3-UC SAP	None	2377°F
374117-3	3300 LCF Cycles	Standard	3-GE APS 3-UC SAP	None	2333°F
372516-3A	350-Hour Endurance Qualification Test	Reduced 20%	6-GE-APS "P" Quality	One Stage 1 Blade Failure at 50% Span at 300 Hours of Endurance	2377°F
207018-8A	Sand Ingestion 50 Hours	Standard	2-Bradellloy 2-GE-APS (P Quality) 2-Solid	More than expected erosion of ceramic	--

all engine tests the shroud casting and machined backing and support were in excellent condition. Cracking of the metal backing, which is typical of current production designs, did not occur with the ceramic shrouds. The trailing edge of the metal backing showed only minor oxidation.

#### 4.2.1 Assurance Testing

##### Engine 374117-2

This was the first T700 engine test conducted with ceramic shrouds. Three ceramic shroud systems, Table 4-2 and Table 4-3, were evaluated in this test. Figures 4-3, 4-4 and 4-5 show the shrouds' condition after engine testing.

TABLE 4-2. Ceramic Shrouds Tested in Engine 374117-2.

<u>Shroud Serial Number</u>	<u>Shroud Position</u>	<u>Coating System</u>
31659	1	GE-VPD <sup>1</sup>
31665	2	GE-APS <sup>2</sup>
31669	3	UC-SAP <sup>3</sup>
31660	4	GE-VPD
31671	5	GE-APS
31674	6	UC-SAP

<sup>1</sup>GE segments produced using the Vacuum Plasma Deposition sprayed NiCrAlY bond coat and composite ZrO<sub>2</sub>-8Y<sub>2</sub>O<sub>3</sub> powder.

<sup>2</sup>GE segments produced using the Air Plasma Deposition sprayed NiCrAlY bond coat and sintered ZrO<sub>2</sub>-8Y<sub>2</sub>O<sub>3</sub> powder.

<sup>3</sup>Union Carbide segments produced using the Shielded Arc Plasma CoNiCrAlY bond coat and fused ZrO<sub>2</sub>-8Y<sub>2</sub>O<sub>3</sub> powder.

TABLE 4-3. Ceramic Shroud Systems Engine Tested on 374117-2.

	<u>GE-APS</u>	<u>GE-VPD</u>	<u>UC-SAP</u>
Bond Coat Composition	Ni22Cr10Al1Y	Ni22Cr10Al1Y	Co32Ni21Cr8A-5Y
Bond Coat Application	Air Plasma	Vacuum Plasma	Shielded Arc
Top Coat Composition Powder	ZrO <sub>2</sub> -8Y <sub>2</sub> O <sub>3</sub>	ZrO <sub>2</sub> -8Y <sub>2</sub> O <sub>3</sub>	ZrO <sub>2</sub> -7Y <sub>2</sub> O <sub>3</sub>
	Sintered and Crushed	Composite	Fused and Crushed
Heat Treat (At 0.012 Inch)	1975F/4 Hours	None	1975F/4 Hours
As Sprayed Ceramic Coating Thickness	0.0440-0.0505	0.0428-0.0483	0.0508-0.0547
Ceramic Coating Thickness After Engine Test (Assembly Ground Shrouds)	0.0301-0.0415	0.0290-0.0430	0.0313-0.0440

The ceramic flowpath of all shrouds had a blackened appearance due to an overtemperature condition in the engine which caused melting of the turbine blade tips. Figure 4-3 shows that there was essentially no coating loss for the GE-APS shroud system, whereas the GE-VPD system shown in Figure 4-4 has coating loss at the shroud ends. The "clean" appearance of the fracture surface of shroud #4 indicates that the fracture occurred during engine disassembly. The other coating spalls on shrouds #1 and #4 (GE-VPD) occurred during the engine test.

After engine testing the shrouds were visually examined at 50X for cracks in the coating and subsequently sectioned for microstructural evaluation. All shrouds showed some degree of laminar cracks in the ceramic coating located parallel to the bond coat surface and approximately 10 mils above the bond coat. In addition, Union Carbide shrouds #6 and #3 had extensive mud-flat cracking of the entire flowpath surface. No mud-flat cracking was observed on GE shrouds. Shrouds #2 and #5 had the least laminar cracking; the cracking was most apparent along the shroud ends and near the corners of the trailing edge. Shrouds #6 and #3 had cracking at the end and along all of the trailing edge of shroud #3 and most of #6. Shrouds #1 and #4 had cracking along the

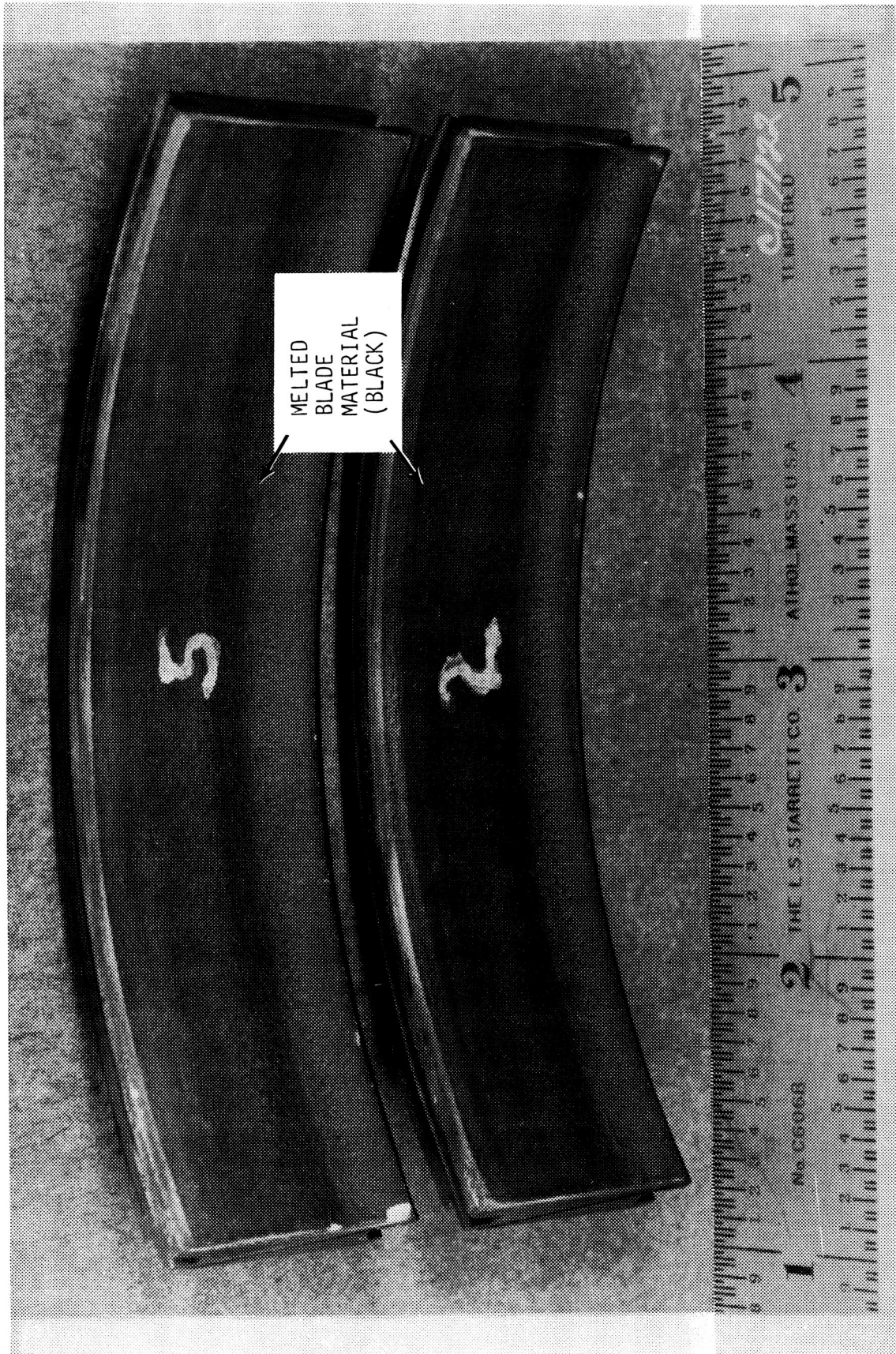


Figure 4-3. Ceramic Shrouds After Testing in Engine 374117-2 -  
GE-APS #2 and #5.



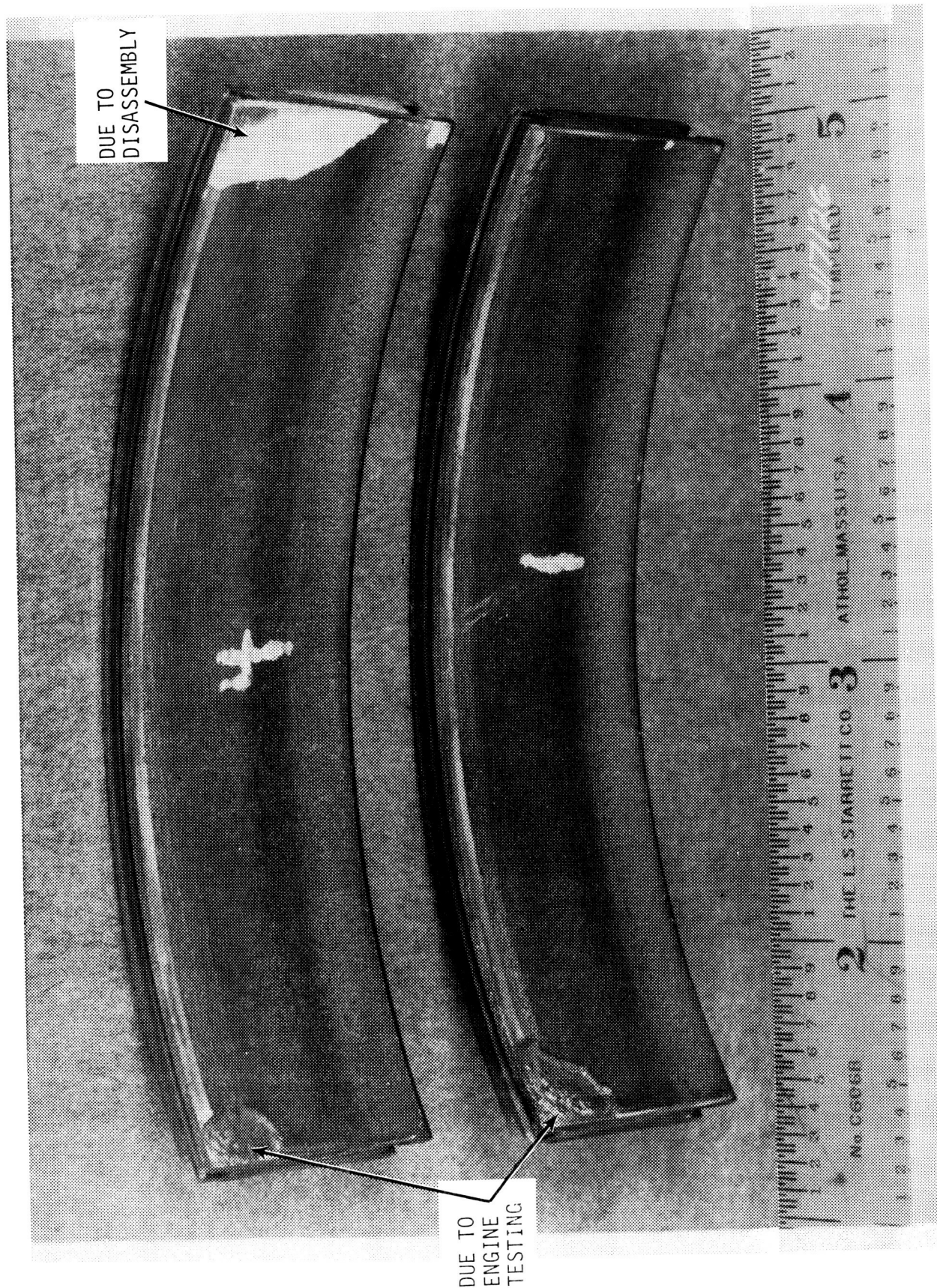


Figure 4-4. Ceramic Shrouds After Testing in Engine 374117-2 -  
GE-VPD #1 and #4.

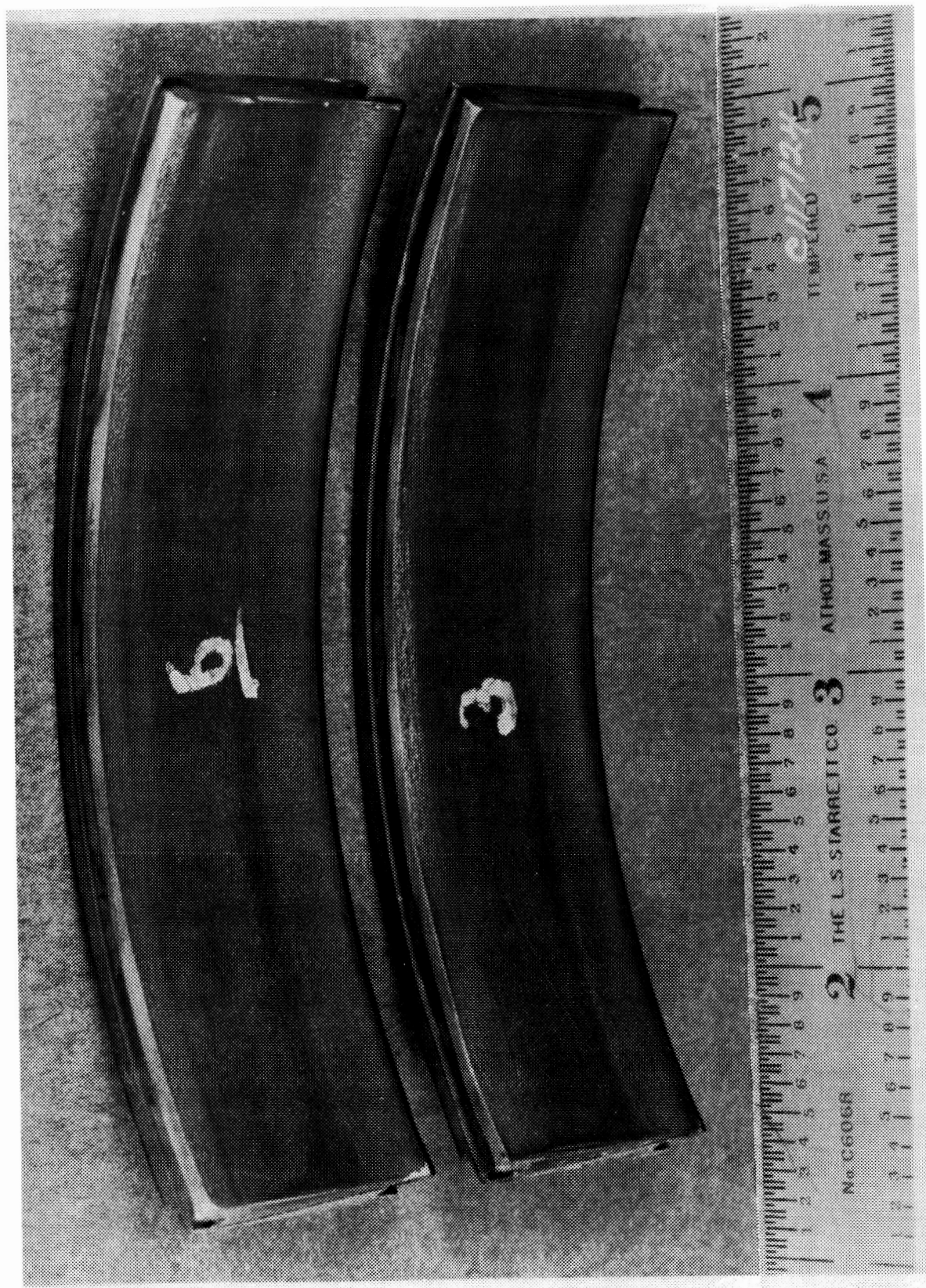


Figure 4-5. Ceramic Shrouds After Testing in Engine 374117-2 -  
UC-SAP #3 and #6.

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entire perimeter of the ends and trailing edge. No laminar cracks were observed at the leading edge; the absence of cracks at the leading edge is due to the angle machined into the cast substrate.

Microstructural evaluation of the three coating systems was also conducted. Cross-sectional views showing the cast substrate, bond coat, and ceramic top coat of each of the three coating systems are presented in Figures 4-6, 4-7, and 4-8. Distinct differences are apparent in both the bond coat and top coat of the three coating systems. The air plasma sprayed NiCrAlY bond coat of Figure 4-6 is quite porous, while the vacuum plasma spray bond coat of Figure 4-7 is much denser. The shielded arc plasma bond coat of Figure 4-8 shows a porosity change for the top 2 mils as a coarser powder which was introduced to produce increased surface roughness. No oxidation of the bond coat was apparent in any of the three systems.

The ceramic top coats also show significant differences in microstructure. All were applied via air plasma; however, spray parameters were varied, as were the starting powders. The ceramic coating porosity decreases from Figures 4-7 to 4-6 to 4-8. The Union Carbide-produced coating shown in Figure 4-8 is quite dense (UC -  $.197 \text{ lb/in}^3$  vs. GE -  $.191 \text{ lb/in}^3$ ), has a much finer pore size, and less visible "splat" boundaries than the GE-produced coatings. The porosity difference between the coatings of Figures 4-6 and 4-7 is attributed to changes in spray parameters and differences in the ceramic powders. The powder used for Figure 4-6 is pre-reacted, sintered 8YSZ ( $\text{ZrO}_2\text{-}8\text{Y}_2\text{O}_3$ ), whereas composite 8YSZ powder was used to produce the coating of Figure 4-7. The vertical crack in the ceramic coating of Figure 4-8 is a cross section view of the mud-flat cracking described earlier. The crack is quite deep, and in some areas the mud-flat cracks progressed almost to the bond coat. Additionally, the vertical cracks could link up with laminar cracks above the bond coat. This propensity for mud-flat cracks and potential linkup with laminar cracks led to the eventual conclusion to drop this system from production consideration.

One other observation is noteworthy from this test. All shroud systems showed a thin, denser layer at the flowpath of the ceramic coating. It is most visible in Figures 4-6 and 4-7 but was also observed for the other coating system. Apparently, the high gas temperatures which caused melting of the



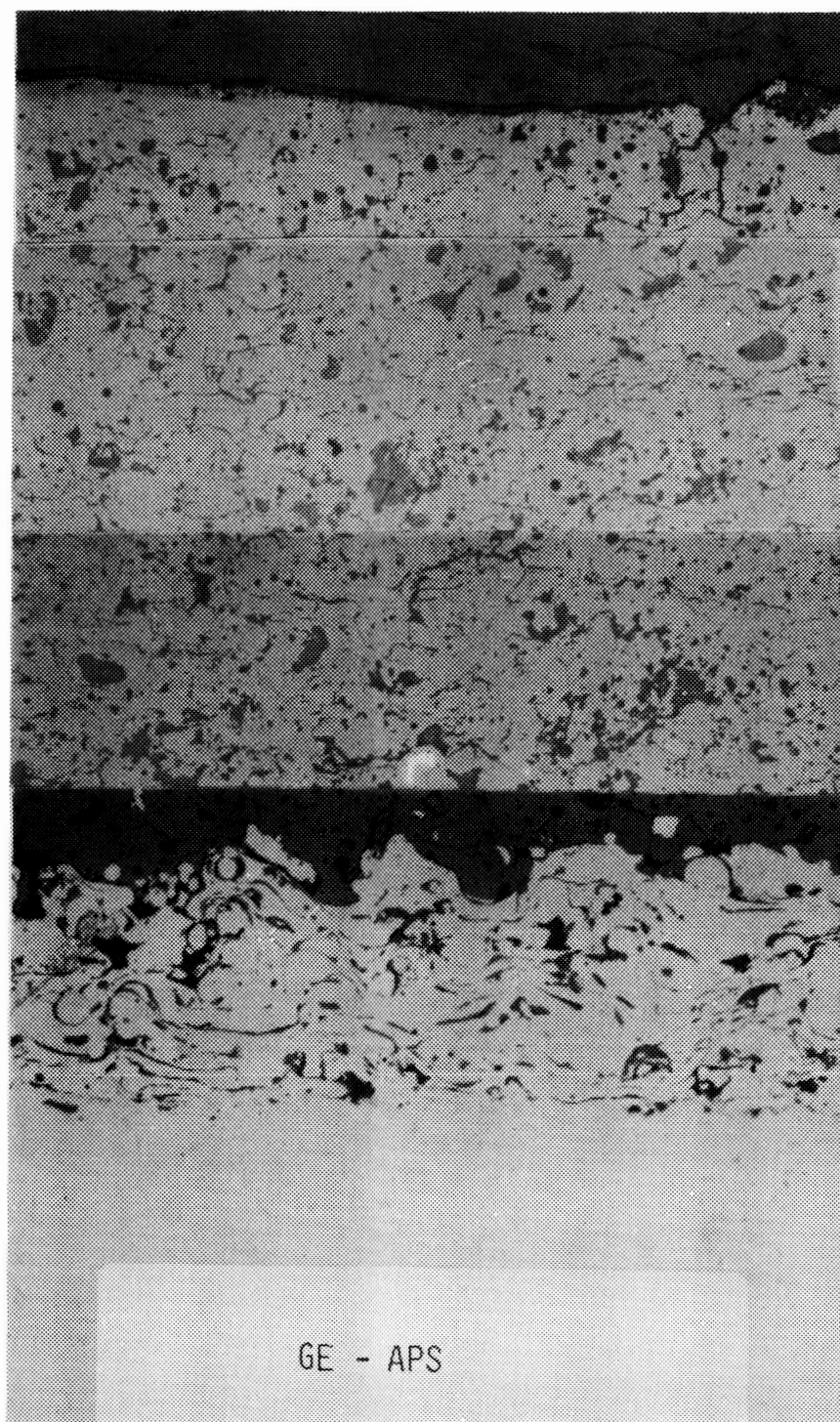


Figure 4-6. Microstructure of GE-APS Shroud #2 (Engine 374117-2).

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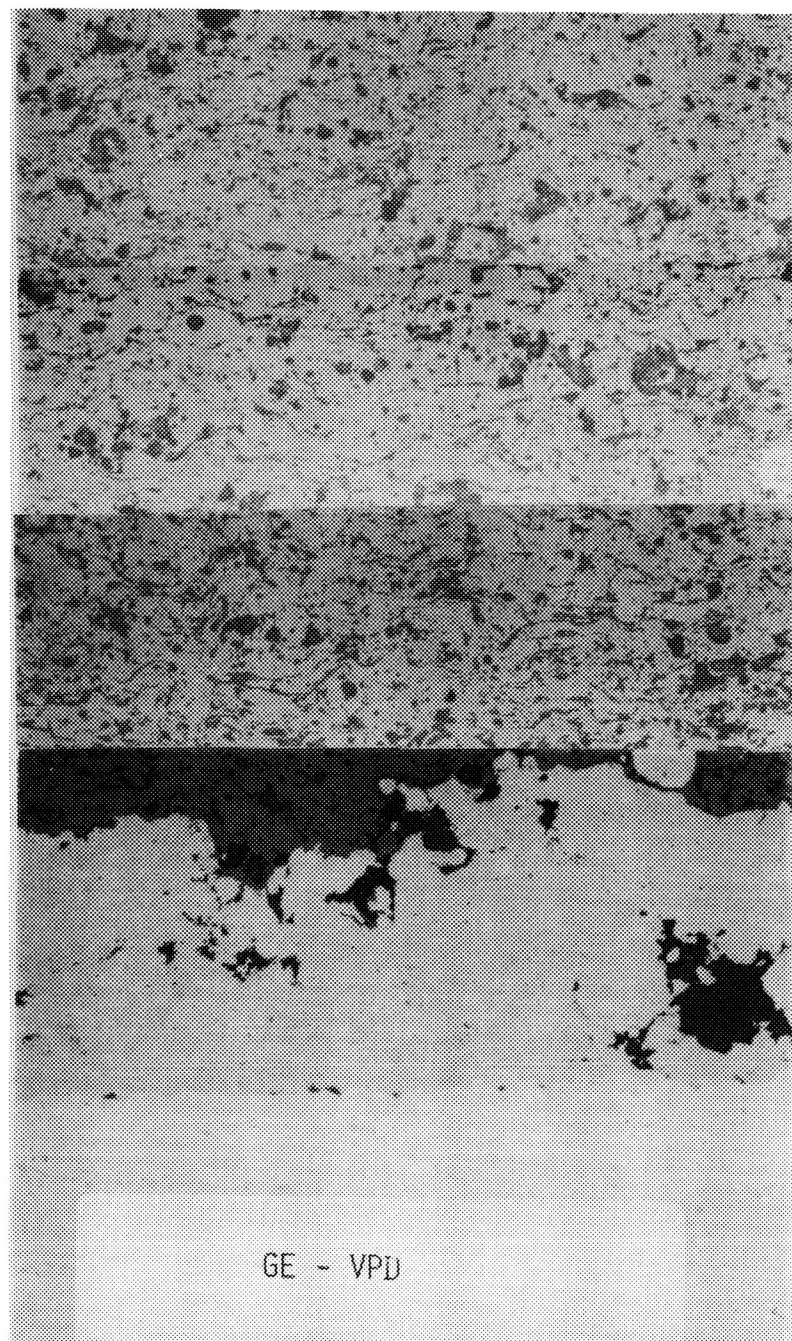


Figure 4-7. Microstructure of GE-VPD Shroud #1 (Engine 374117-2).

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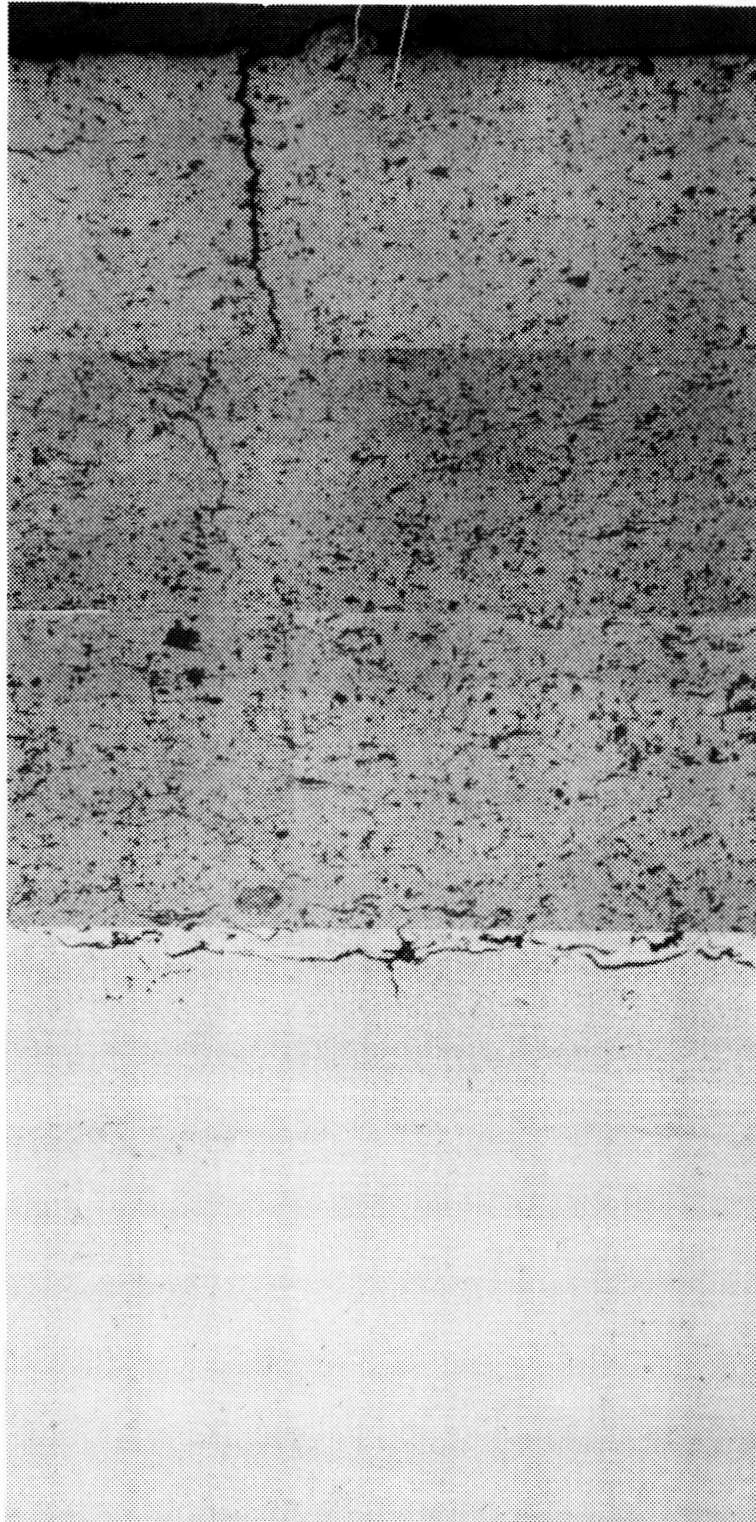


Figure 4-8. Microstructure of UC-SAP Shroud #6 (Engine 374117-2).

blade tips also caused sintering of the ceramic coating at the flowpath surface. Sintering was not observed in subsequent engine tests and was not a detrimental occurrence in this test.

Some blade/shroud rubbing did occur during the test and resulted in small amounts of blade material being transferred to the shroud surface. This "scabbing" is visible in the cross section view shown in Figure 4-9; EDAX analysis determined the scab to be oxidized blade material on the ceramic flowpath.

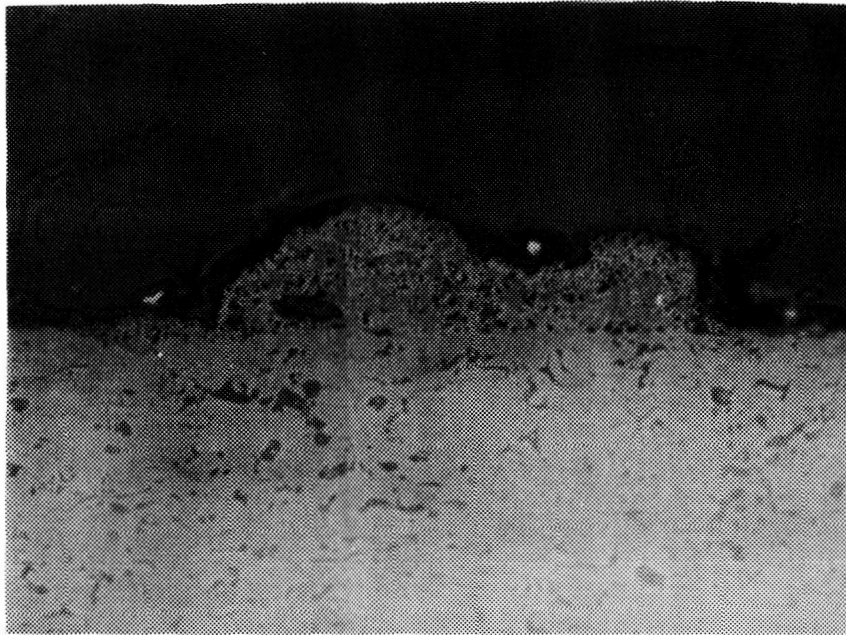
### Conclusions

- Ceramic shrouds performed well in engine test
- Demonstrated 20% reduction in cooling flow
- Ceramic shrouds exhibit minimal spalling even though there is edge cracking
- GE-APS system best
- GE-VPD system performance not acceptable and dropped from program
- Shroud backing and support in excellent condition.

### Engine 212108-4

This engine evaluated three shrouds each of the GE-APS NiCrAlY/pre-reacted, sintered 8YSZ and Union Carbide UC-SAP CoNiCrAlY/7YSZ shroud systems. The shroud serial numbers and position in the engine are detailed in Table 4-4. Photographs of the shrouds after engine testing are presented in Figures 4-10 through 4-12. The GE-coated shrouds shown in Figures 4-10 and 4-11 have slight spallation at the end. The Union Carbide shrouds shown in Figure 4-12 have no spallation but do have extensive mud-flat cracking. The Union Carbide shrouds have considerably more laminar cracking of the ceramic coating than do the GE shrouds. The three Union Carbide shrouds had laminar cracking along both ends and most of the trailing edge, whereas GE Shrouds #1 and #3 had only a few short, discontinuous segments of cracking. GE Shroud #5 had slightly longer cracks than Shrouds #1 and #3, but this was still considerably less than the best Union Carbide shroud.

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BLADE TRANSFER

8YSZ

Figure 4-9. Photomicrograph Showing Blade Material Transfer to Ceramic Flowpath Due to Blade Rub (Engine 374117-2).

TABLE 4-4. Ceramic Shrouds Tested in Engine 212108-4.

<u>Shroud Serial Number</u>	<u>Shroud Position</u>	<u>Coating System</u>
65731	1	GE-APS <sup>1</sup>
65745	2	UC-SAP <sup>2</sup>
65739	3	GE-APS
65749	4	UC-SAP
65741	5	GE-APS
65752	6	UC-SAP

- <sup>1</sup> GE segments produced using the air plasma deposition sprayed NiCrAlY bond coat and sintered  $ZrO_2-8Y_2O_3$  powder.
- <sup>2</sup> Union Carbide segments produced using the shielded arc plasma CoNiCrAlY bond coat and fused  $ZrO_2-7Y_2O_3$  powder.

Microstructural examination of these shrouds revealed results similar to the previous engine test. That is, the Union Carbide bond coat and top coat are both more dense than the GE coating; also, the Union Carbide coating has considerably more cracking. Figure 4-13 illustrates the extensive laminar cracking of the Union Carbide coating and also the link-up of vertical and laminar cracking. This view is of the shroud end and portrays a worst case. Figure 4-14 shows a laminar crack in the GE coating at the shroud end; the crack length is only 15 mils compared to the 30-mil crack at a similar position in Figure 4-13 of a Union Carbide shroud. No bond coat oxidation was detailed on either shroud system. Additionally, there was no sintering of the ceramic flowpath surface as observed in the previous test.

The GE shrouds of this test were prone to loss of coating beneath the flowpath, Figure 4-15. This loss occurred primarily at the shroud ends and may be due to an airflow peculiarity or processing irregularity during coating application. It was not observed in other tests.



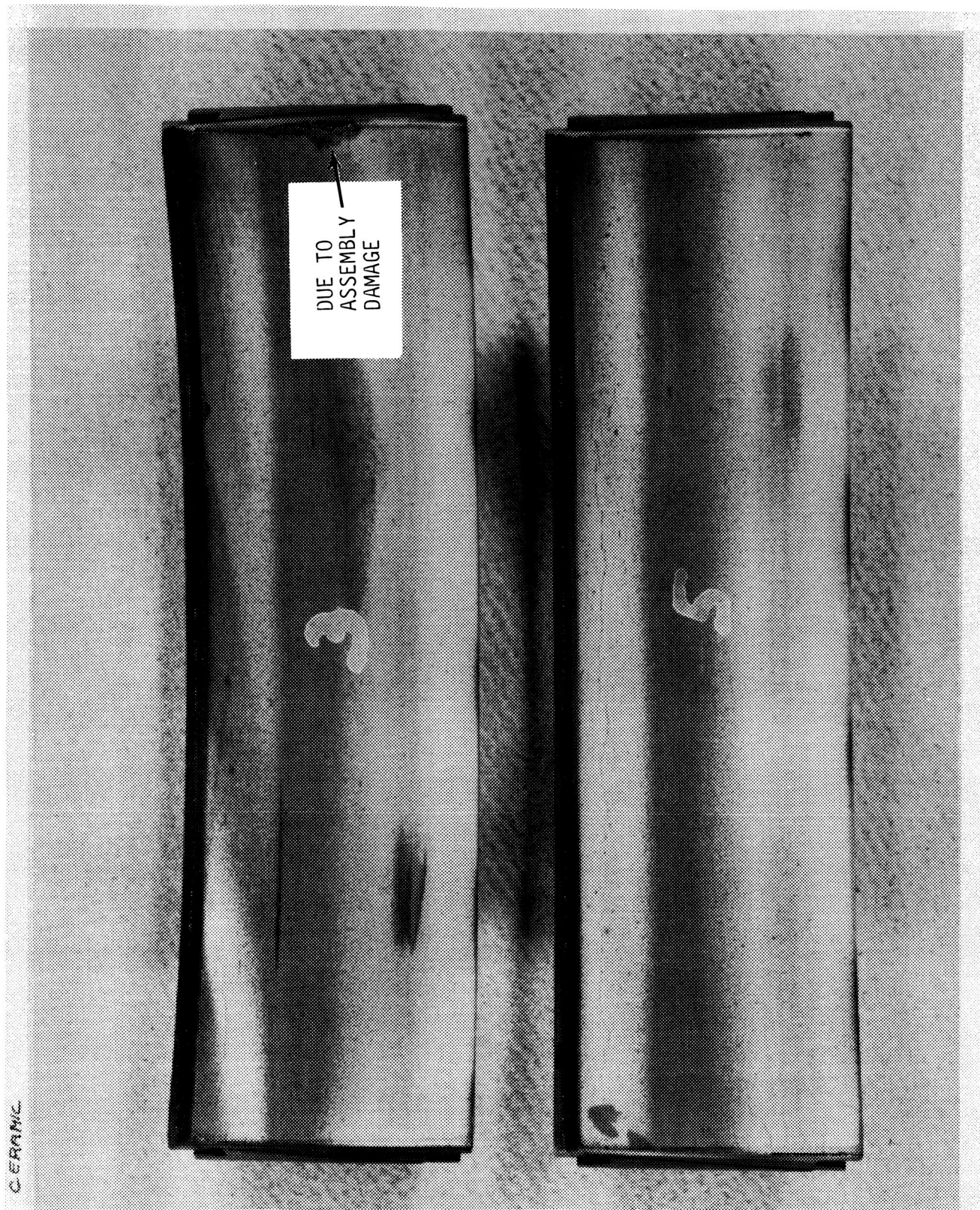


Figure 4-10. Ceramic Shrouds After Testing in Engine 212108-4 -  
GE-APS #3 and #5.

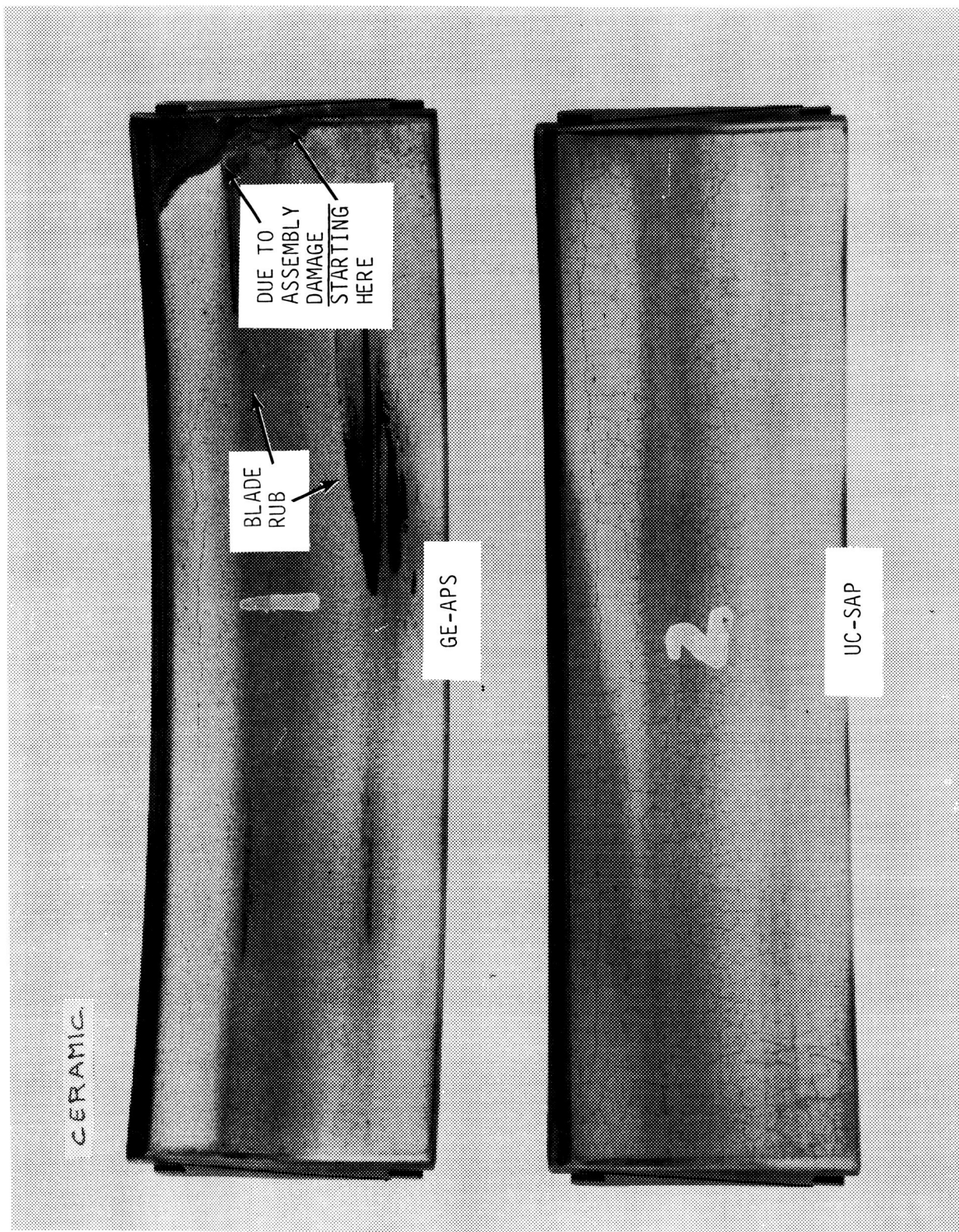


Figure 4-11. Ceramic Shrouds After Testing in Engine 212108-4 - GE-APS #1 and UC-SAP #2.



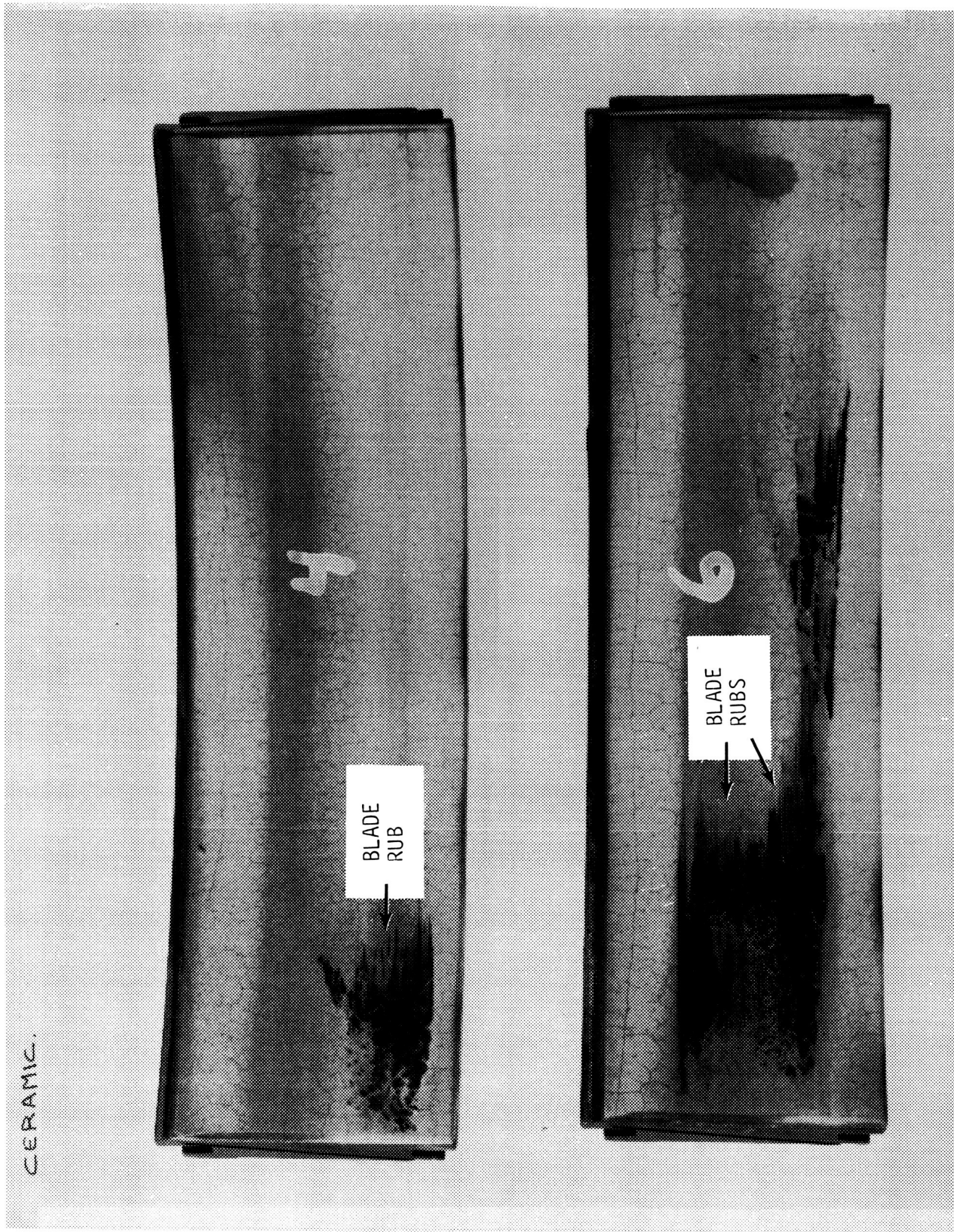
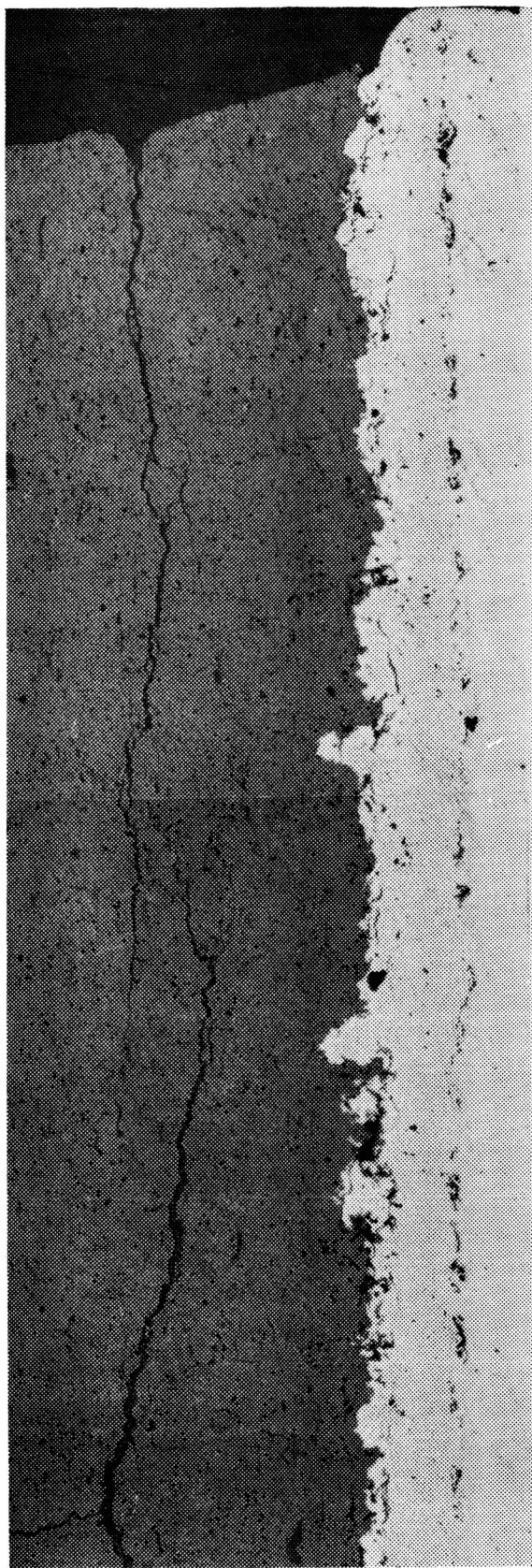
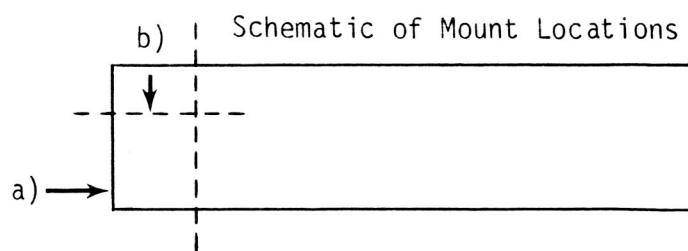
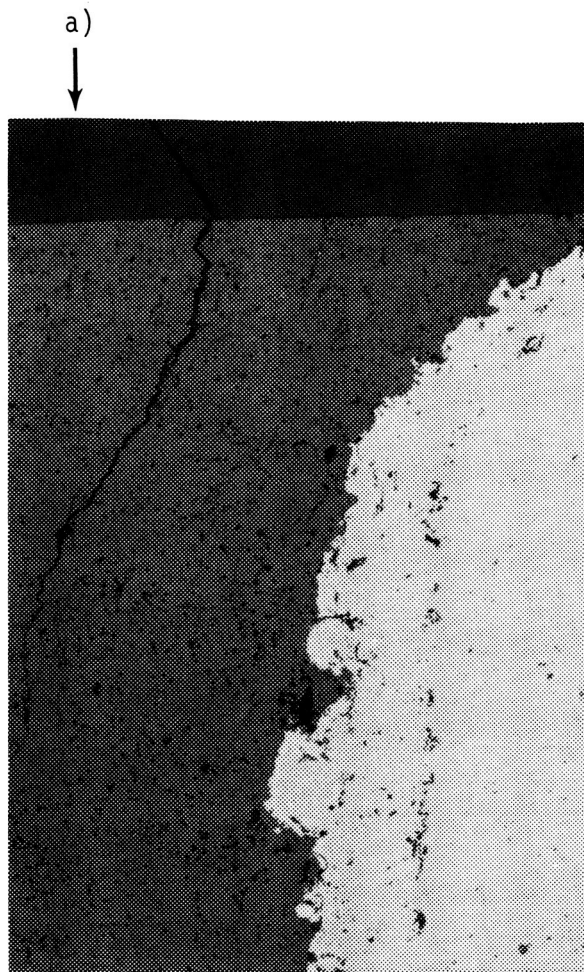


Figure 4-12. Photograph of UC-SAP #4 and #6 (Engine 212108-4)





← b)



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- a) View Parallel to Shroud End
- b) View Perpendicular to (a) showing crack depth into the shroud

Figure 4-13. Microstructure of UC-SAP Shroud #4 Showing Extensive Cracking (Engine 212108-4).

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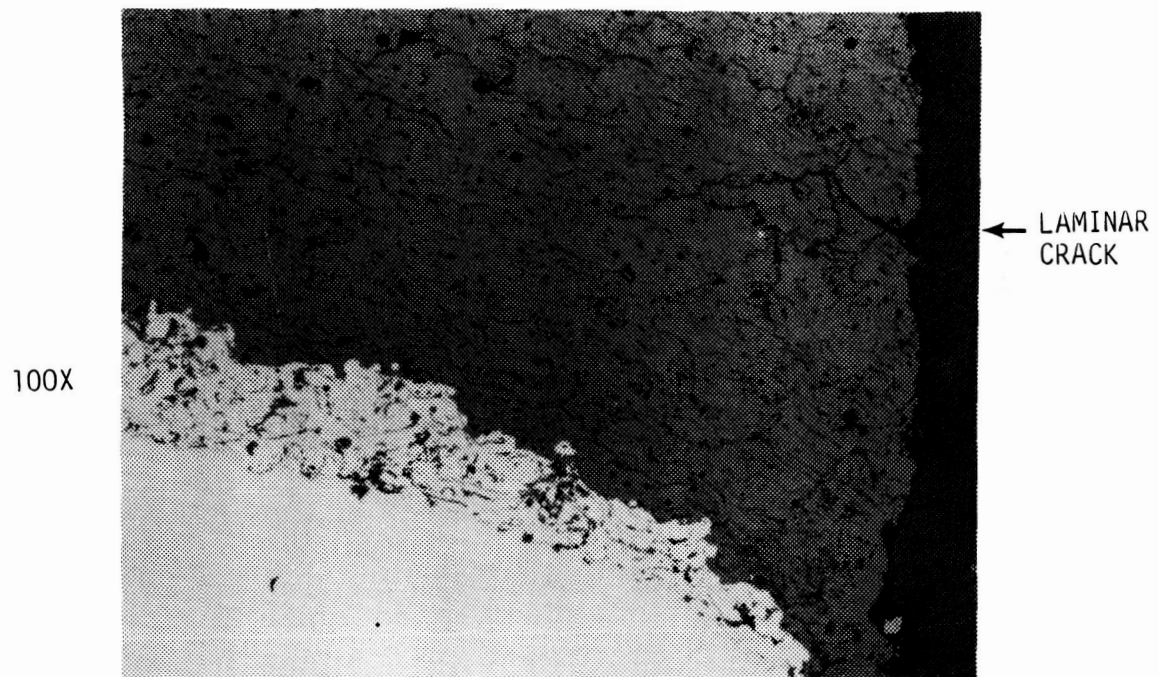


Figure 4-14. Microstructure of GE-APS Shroud #5 (Engine 212108-4).

3.5X

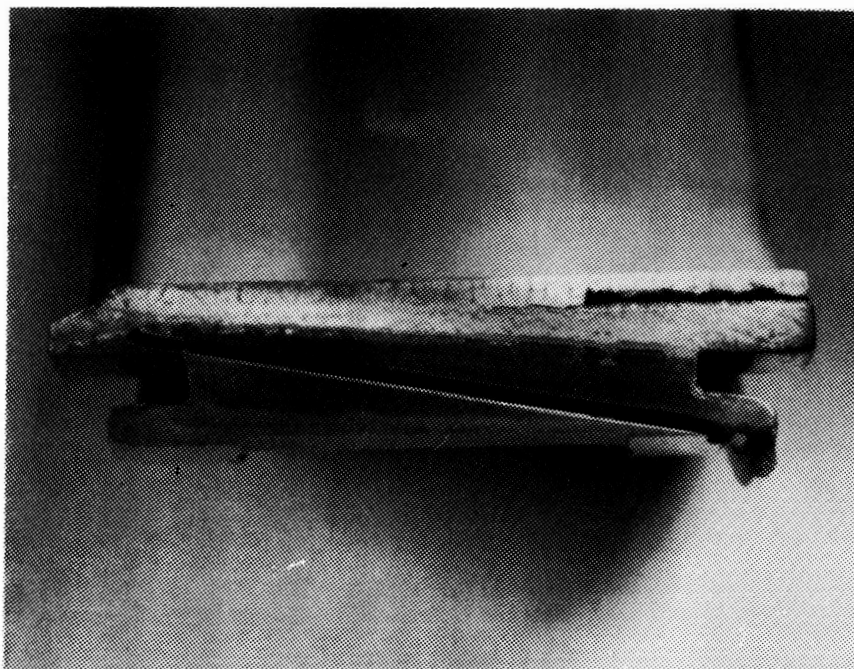


Figure 4-15. Photograph of Circumferential End of GE-APS Shroud #5 Showing Loss of Coating Beneath Flowpath (Engine 212108-4).

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### Engine 374117-3

This engine ran three ceramic shrouds each of the GE and Union Carbide shroud systems for 3300 LCF cycles at standard shroud cooling flows, Table 4-5.

TABLE 4-5. Ceramic Shrouds Tested in Engine 374117-3.

<u>Shroud Serial Number</u>	<u>Shroud Position</u>	<u>Coating System</u>
65738	1	GE-APS <sup>1</sup>
65742	2	UC-SAP <sup>2</sup>
65737	3	GE-APS
65747	4	UC-SAP
65735	5	GE-APS
65744	6	UC-SAP

<sup>1</sup> GE segments produced using the Air Plasma Deposition sprayed NiCrAlY bond coat and sintered  $ZrO_2-8Y_2O_3$  powder.

<sup>2</sup> Union Carbide segments produced using the Shielded Arc Plasma CoNiCrAlY bond coat and fused  $ZrO_2-7Y_2O_3$  powder.

Visual examination showed GE Shrouds #1 and #3 to be in near perfect condition with no spallation and almost no laminar cracking. Shroud #5 had coating spall at one end and slight laminar cracking at the other end. Photographs of all shrouds are shown in Figures 4-16 through 4-20. All three Union Carbide shrouds had coating spallation which occurred during disassembly as evidenced by the clean fracture surfaces. Laminar cracking of the Union Carbide shrouds was less than on previous tests but still worse than the GE shrouds of this test. The Union Carbide shrouds had mud-flat cracking as in the previous tests.

The microstructural features of these shrouds were very similar to the previous tests and, hence, no new photographs are presented. There was no oxidation of the bond coat or sintering of the ceramic flowpath.



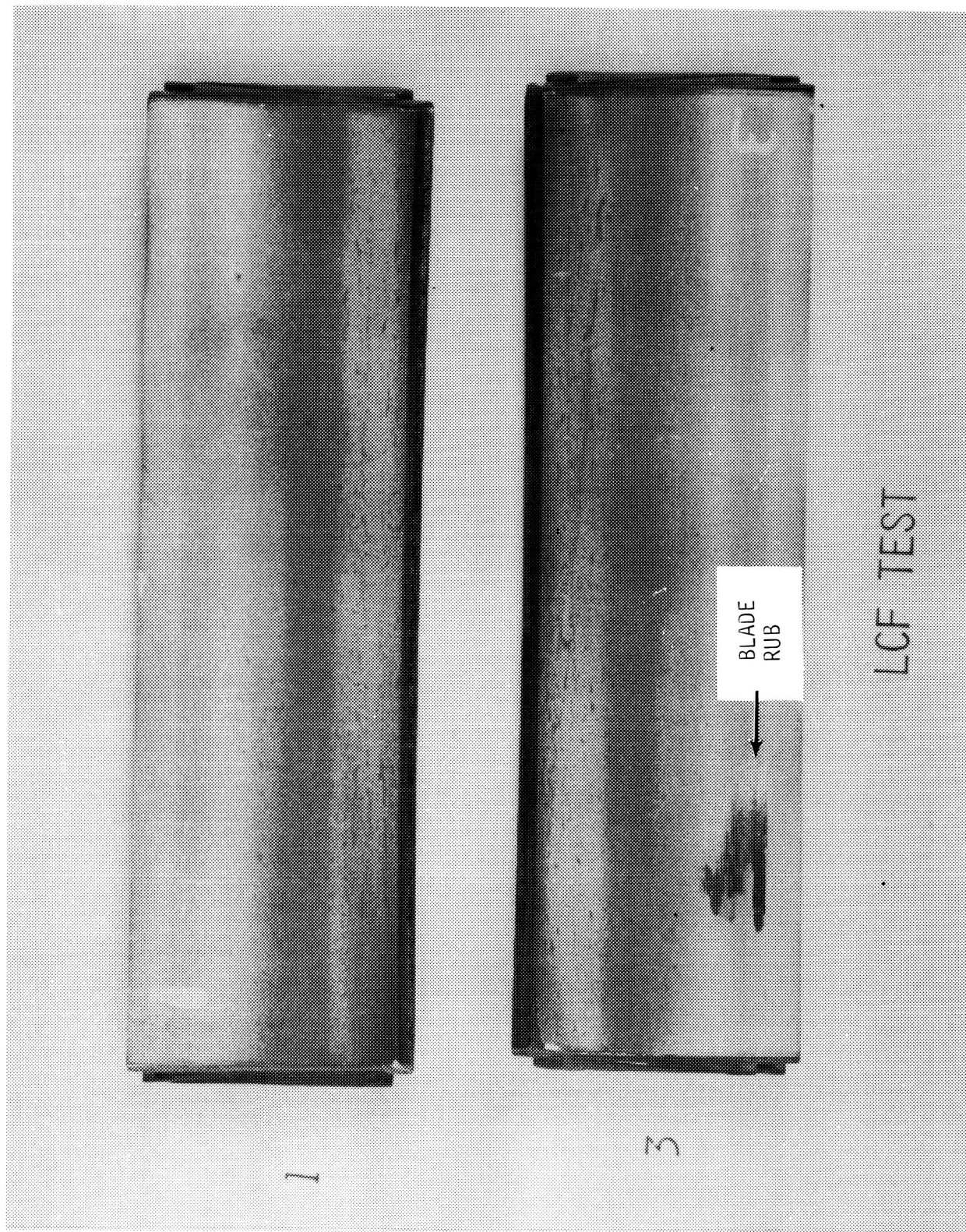


Figure 4-16. Ceramic Shrouds After Testing in Engine 374117-3 -  
GE-APS #1 and #3.

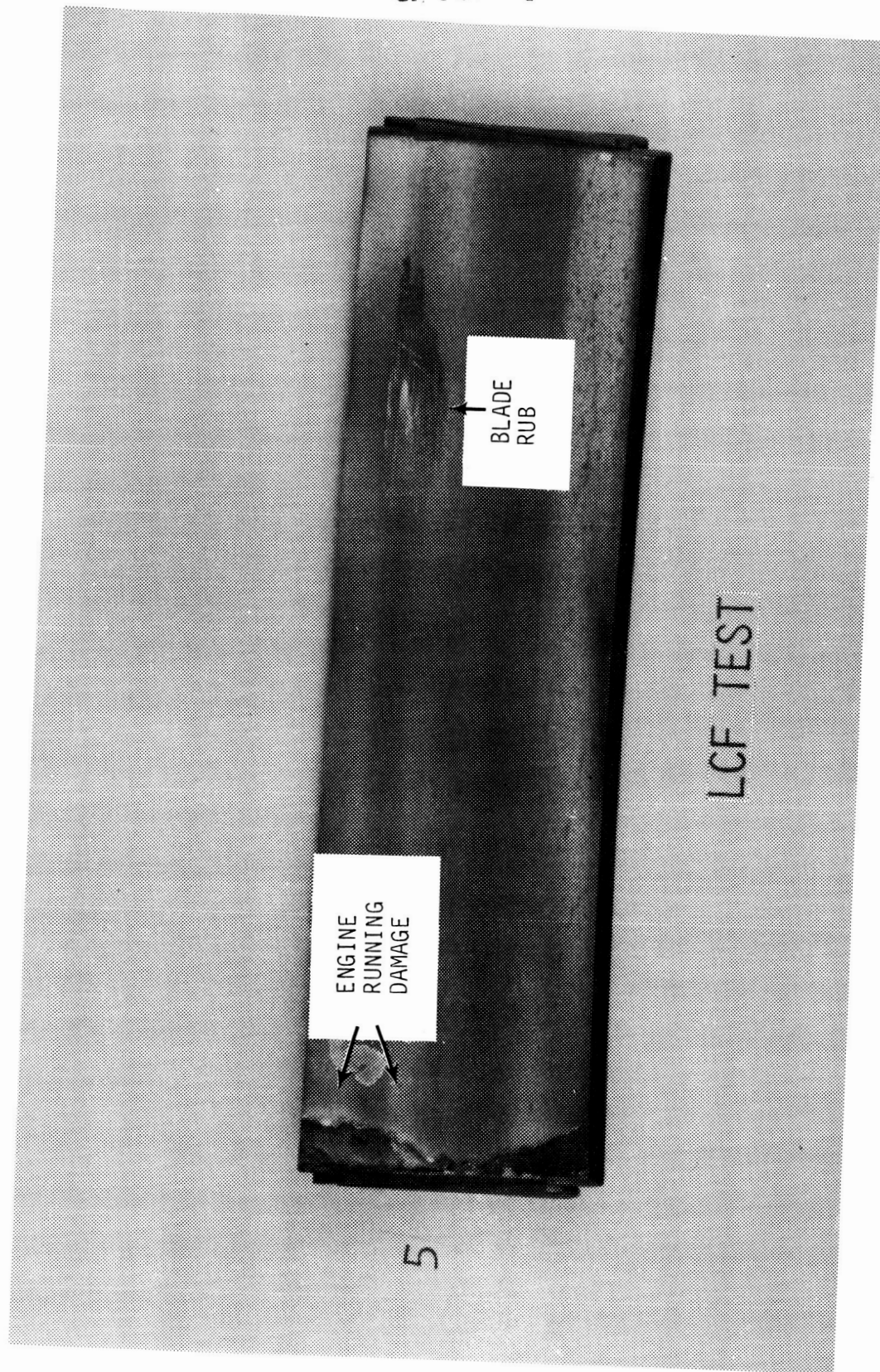
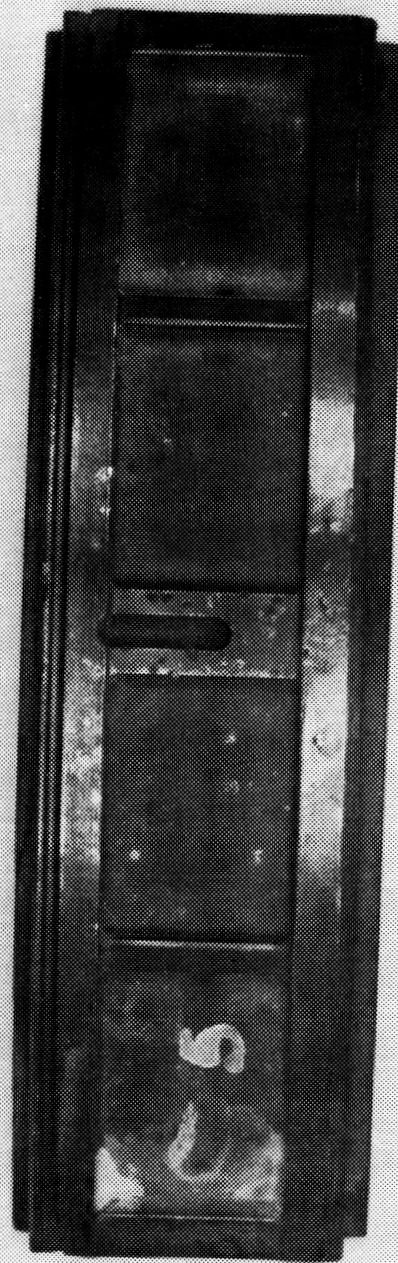


Figure 4-17. Ceramic Shrouds After Testing in Engine 374117-3 -  
GE-APS #5.





LCF TEST

Figure 4-18. Ceramic Shrouds After Testing in Engine 374117-3 -  
GE-APS #5 (Backing).

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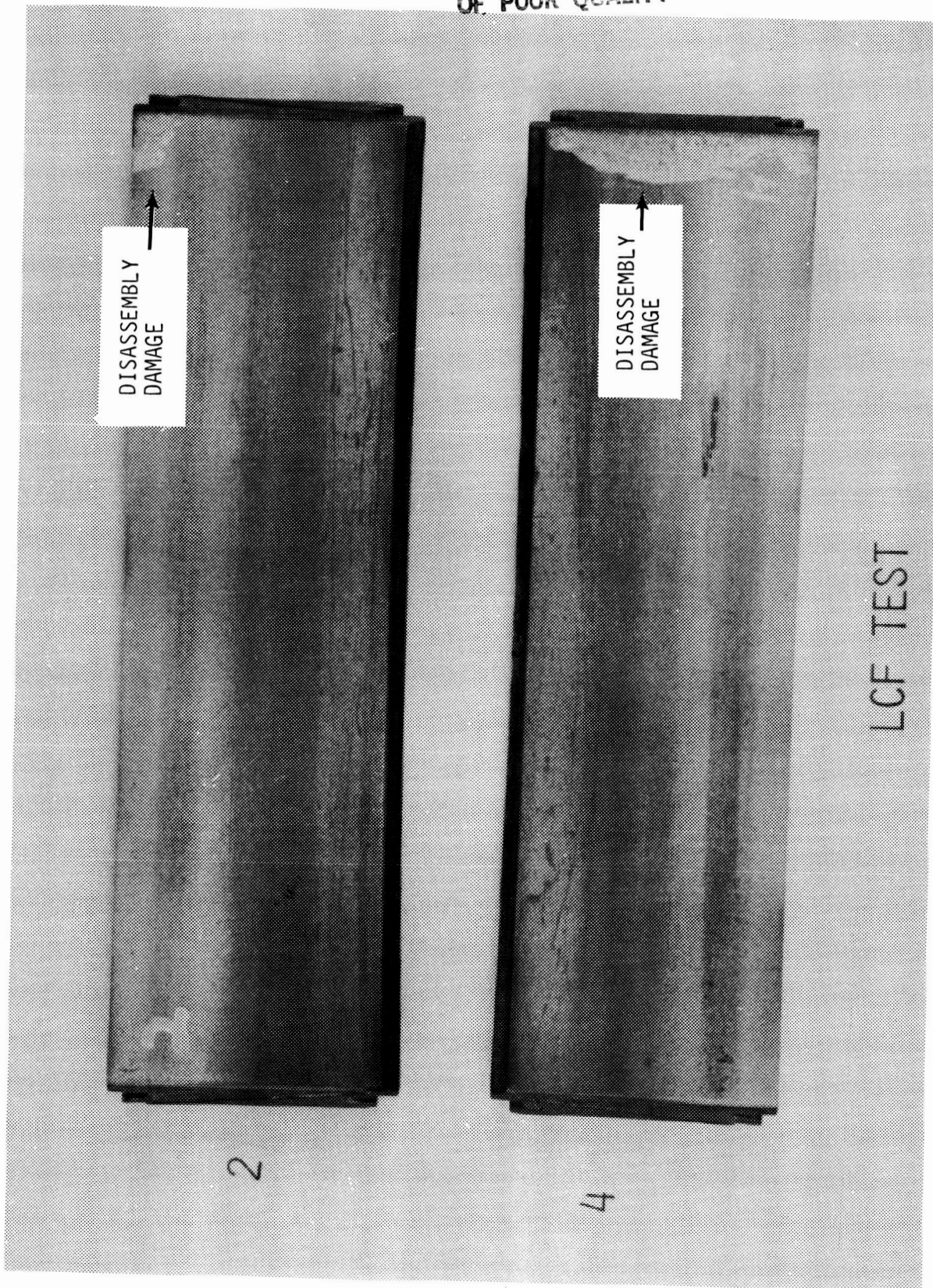


Figure 4-19. Ceramic Shrouds After Testing in Engine 374117-3 -  
UC-SAP #2 and #4.



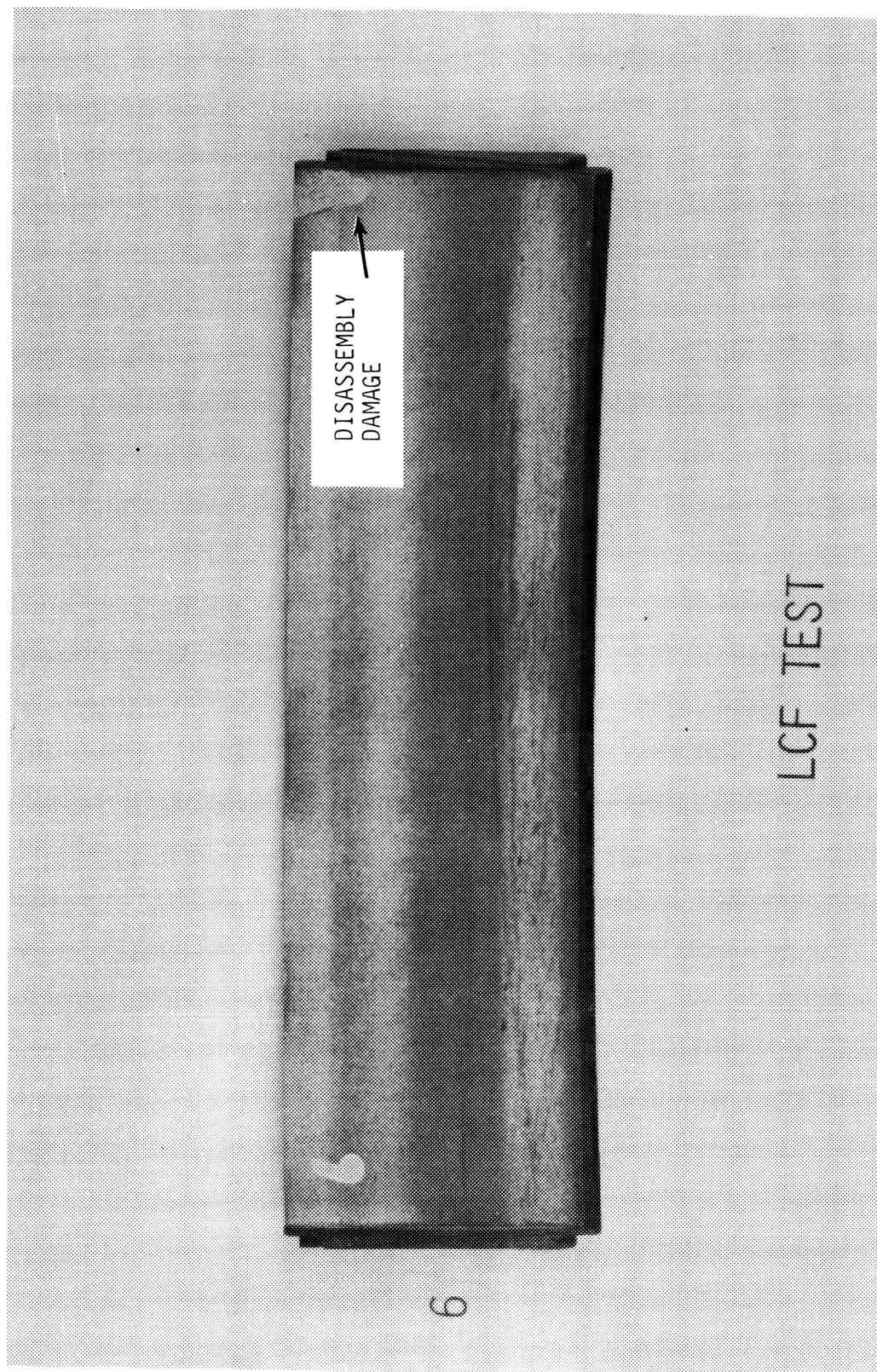


Figure 4-20. Ceramic Shrouds After Testing in Engine 374117-3 -  
UC-SAP #6.

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#### 4.2.2 Qualification Test

##### Engine 372516-3

This 350-hour endurance test qualified the GE-APS ceramic shroud for production on the T700 engine. The six shrouds are detailed in Table 4-6. All six shrouds were manufactured and approved to GE Specification F50TF60. The engine was operated with a 20% Stage 1 shroud cooling flow reduction. A significant event occurred during the last phase of engine testing: one Stage 1 blade failed at about 50% span after 300 endurance hours. The failed Stage 1 blade was replaced and the last 50 hours of endurance testing was completed.

TABLE 4-6. Ceramic Shrouds Tested in Engine 372516-3A.

<u>Shroud Serial Number</u>	<u>Shroud Position</u>	<u>Coating System</u>
93122	1	GE-APS <sup>1</sup>
93127	2	GE-APS
93104	3	GE-APS
93105	4	GE-APS
93128	5	GE-APS
93120	6	GE-APS

<sup>1</sup> GE segments produced using the air plasma deposition sprayed NiCrAlY bond coat and sintered ZrO<sub>2</sub>-8Y<sub>2</sub>O<sub>3</sub> powder.

Visual examination showed all six GE shrouds to be in near-perfect condition even after sustaining impact from the Stage 1 blade failure.

Engine 372516-3 was a unique engine test. This engine was a production T700-401 engine. The engine was first broken in and performance tested with current production hardware (not ceramic shrouds). The engine was then rebuilt with a number of performance improvement hardware changes, one of

which was ceramic stage 1 shrouds. The engine was then performance tested again (back-to-back test) and showed a significant performance increase. Based on this back-to-back engine testing, the engine performance increase due to ceramic shrouds was calculated to be an increase in engine SHP at IRP of .5% and a reduction in SFC at 60% MC of .3%.

The amount of laminar cracking was minimal in all of these shrouds (Figures 4-21 through 4-29). Only Shrouds #2 and #5 had cracking along the trailing edge; the other shrouds had none. No cracking at all was observed for Shroud #4. Shroud #3 had one small 0.030 inch long crack at one corner, and Shrouds #1 and #6 had slight cracking at the corners or at the shroud end.

The extent of the cracks into the coating of shroud #2 is illustrated in Figures 4-30a and b. Figure 4-30a shows crack length for the shroud end while Figure 4-30b shows the crack at the trailing edge. In both occurrences the crack length is approximately 50 mils and, more importantly, the crack angles toward the shroud surface rather than staying parallel to the bond coat. This minimizes the potential for large areas of coating loss.

Analysis of the shroud/blade rub area of shroud #2 was conducted using SEM/EDAX. These results are shown in Figures 4-31a and b. Figure 4-31a shows a cross section view of the ceramic coating and rub area, while Figure 4-31b is an enlarged view identifying where EDAX analysis was carried out. The EDAX results are presented in Figures 4-32a, b, c and d. EDAX spot "0", Figure 4-32a, showed only Y and Zr and no diffusion of metallic species into the ceramic coating. EDAX 1, Figure 4-32b, shows elemental species common in the blade tip material but does have high Zr, indicating some diffusion from the ceramic coating into the rub area or smearing during polishing. The EDAX analysis of spots 2 and 3 presented in Figures 4-32c and d, respectively, reveals the elemental species of the blade; the high Al peak for Figure 4-32d indicates oxidation of the rub material.

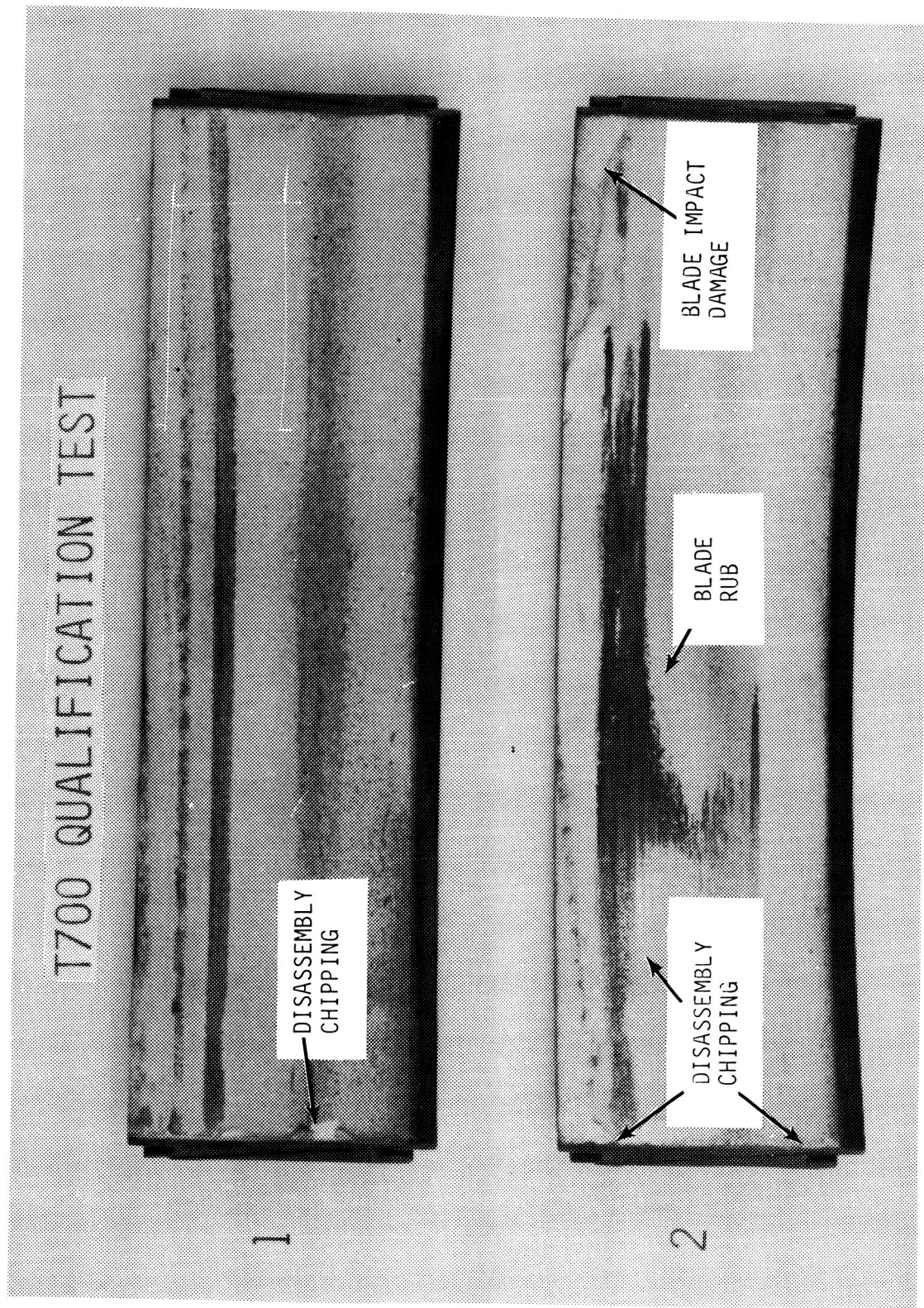


Figure 4-21. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #1 and #2.



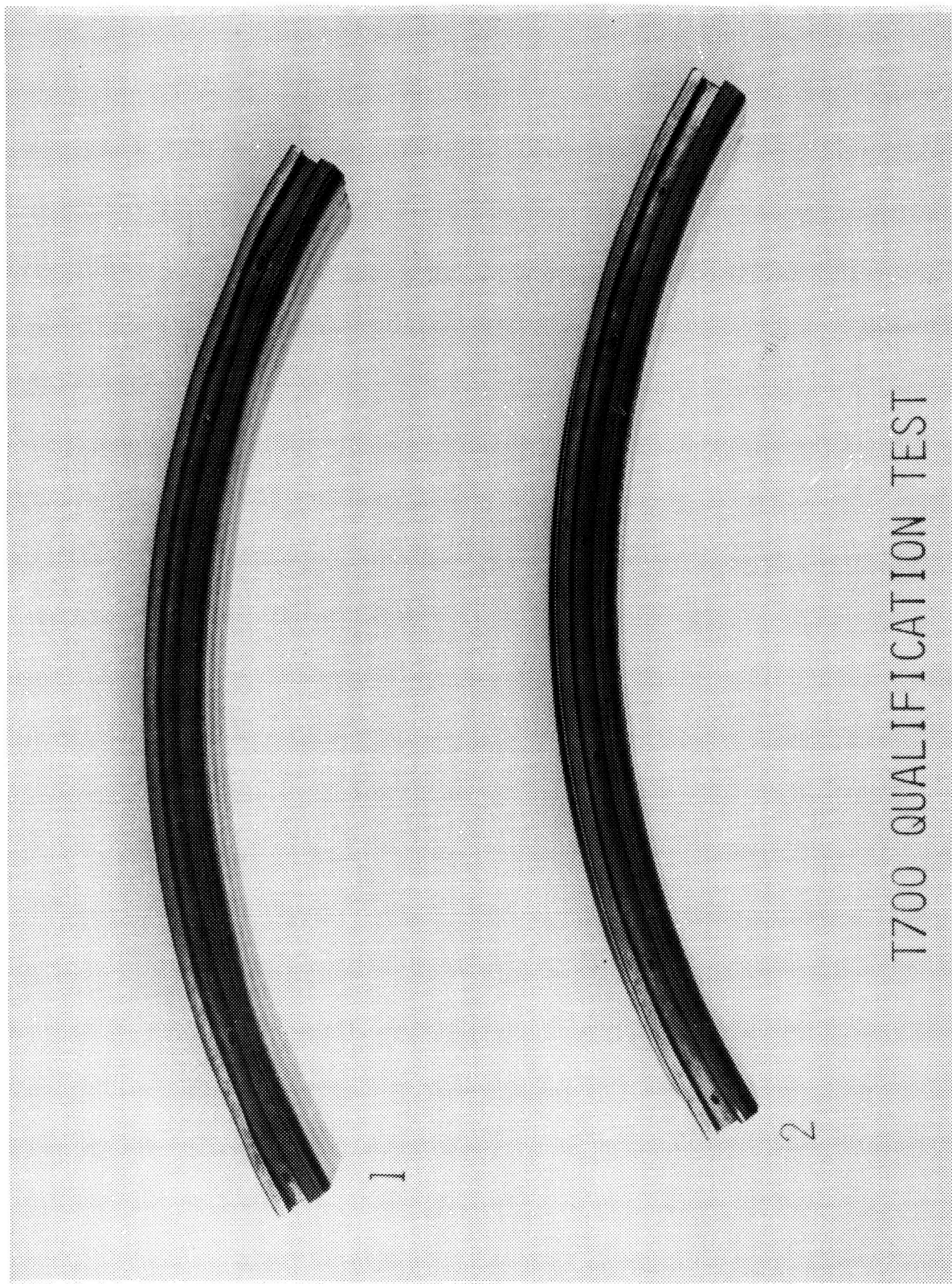


Figure 4-22. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #1 and #2 (End View).

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# T700 QUALIFICATION TEST

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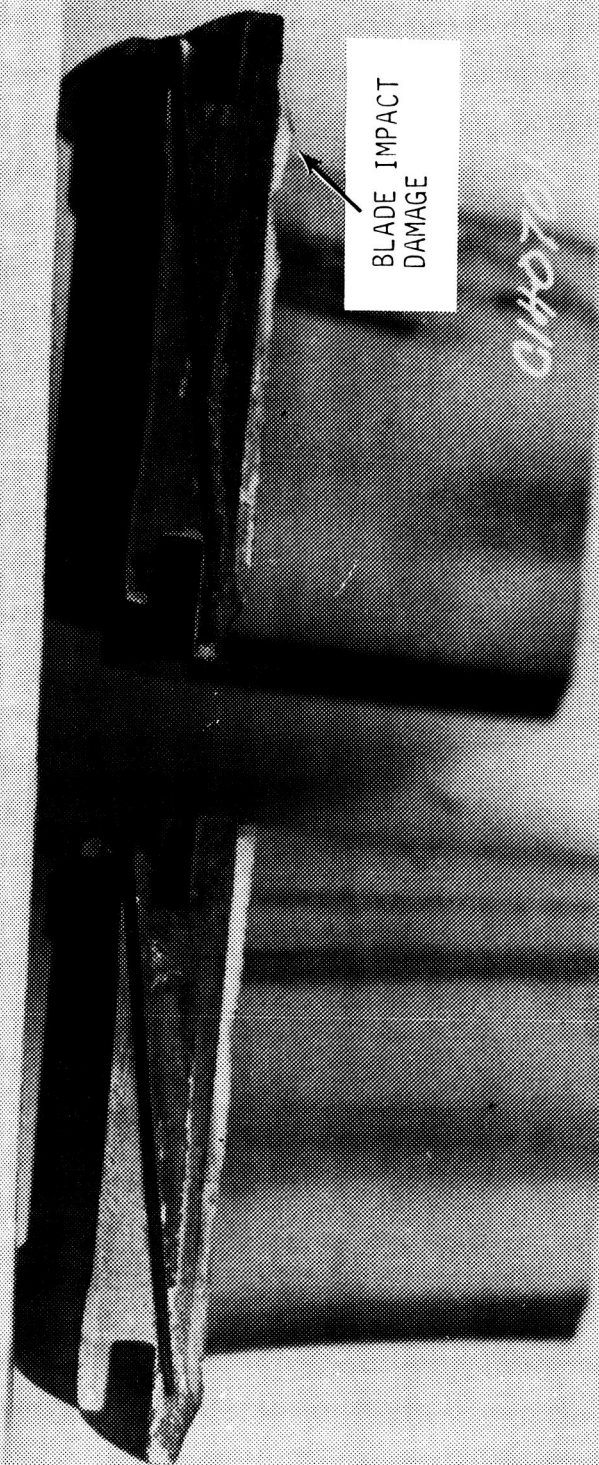


Figure 4-23. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #1 and #2 (Aft View).



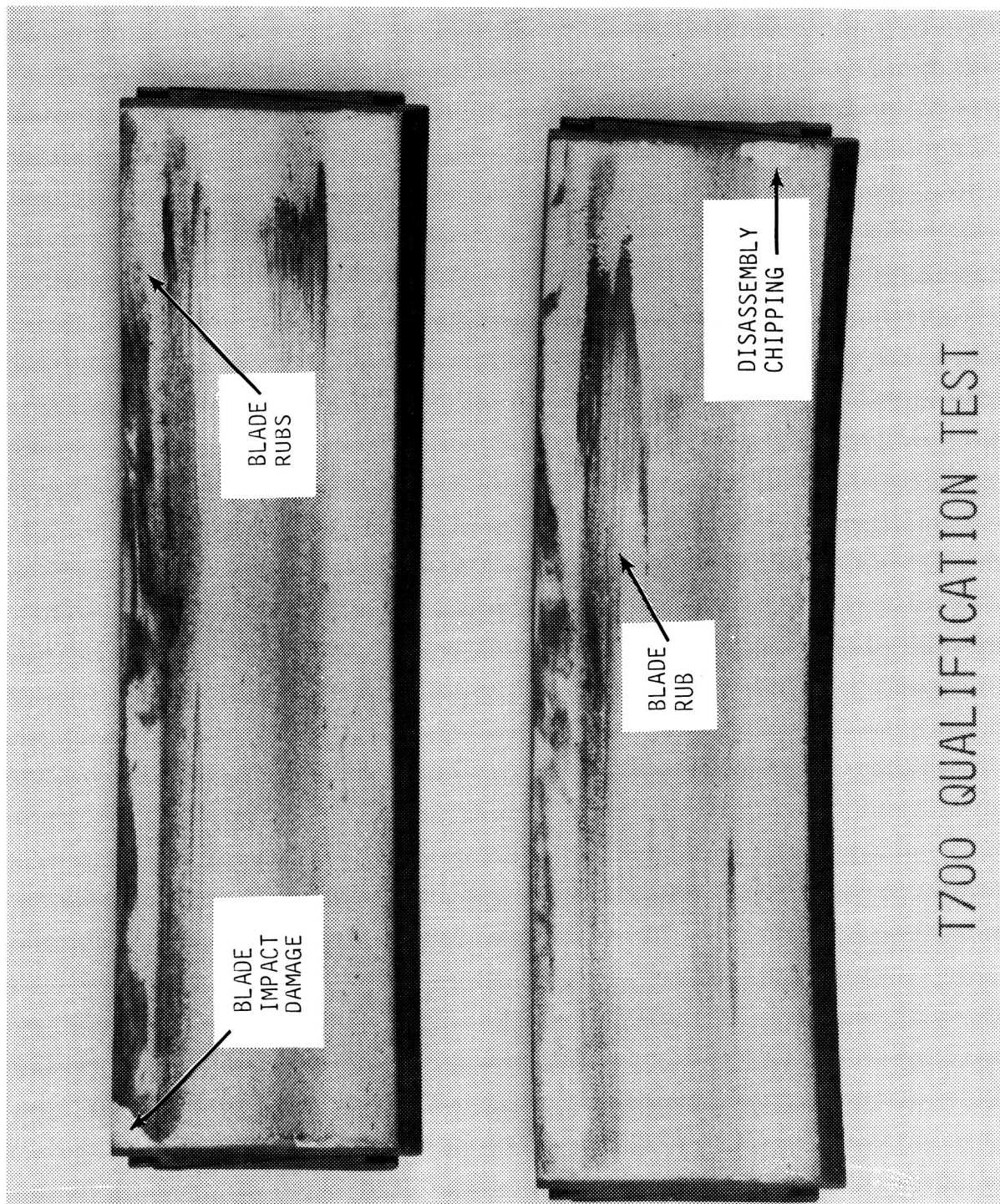


Figure 4-24. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #3 and #4.

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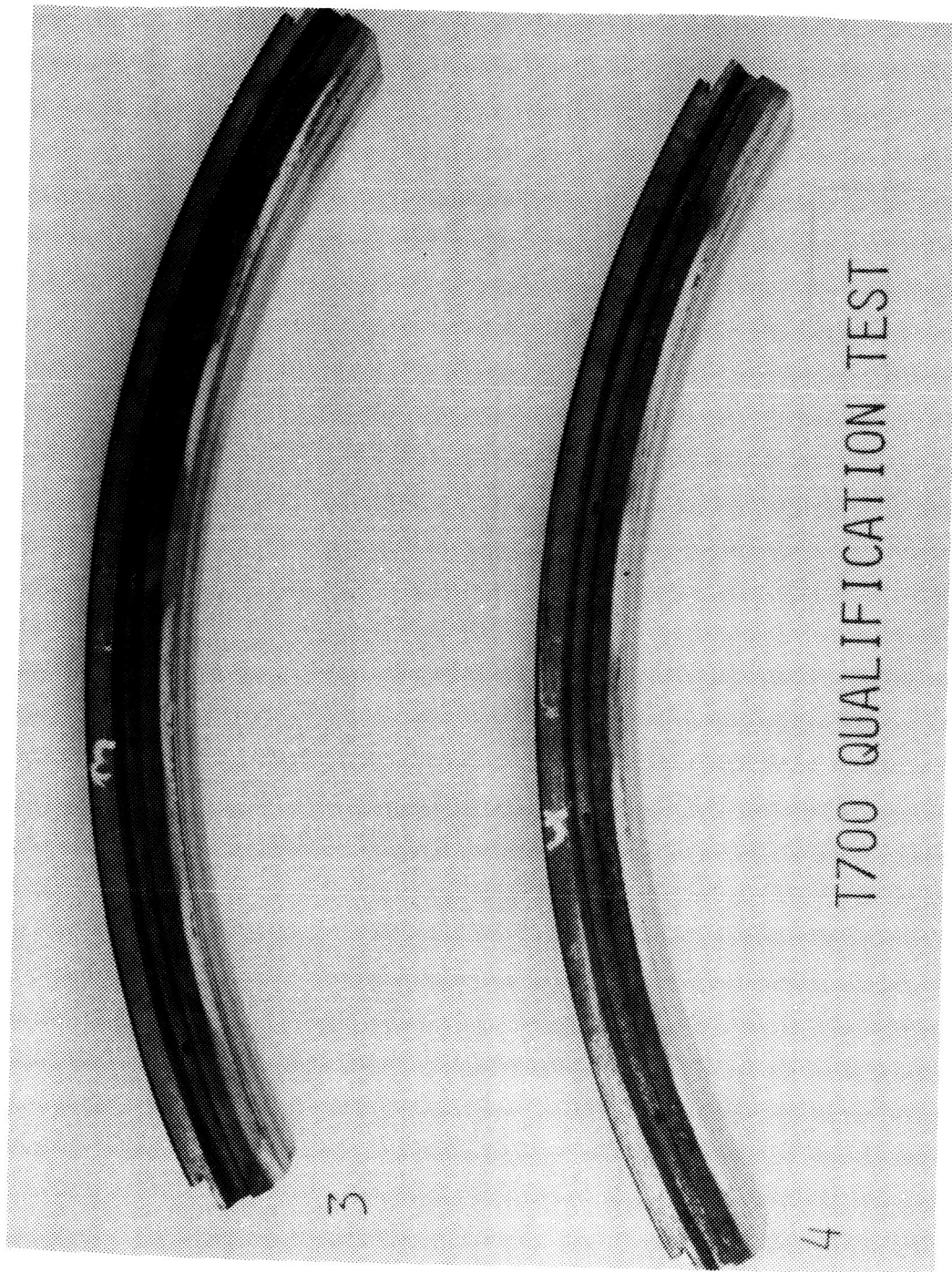


Figure 4-25. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #3 and #4 (End View).



# T700 QUALIFICATION TEST

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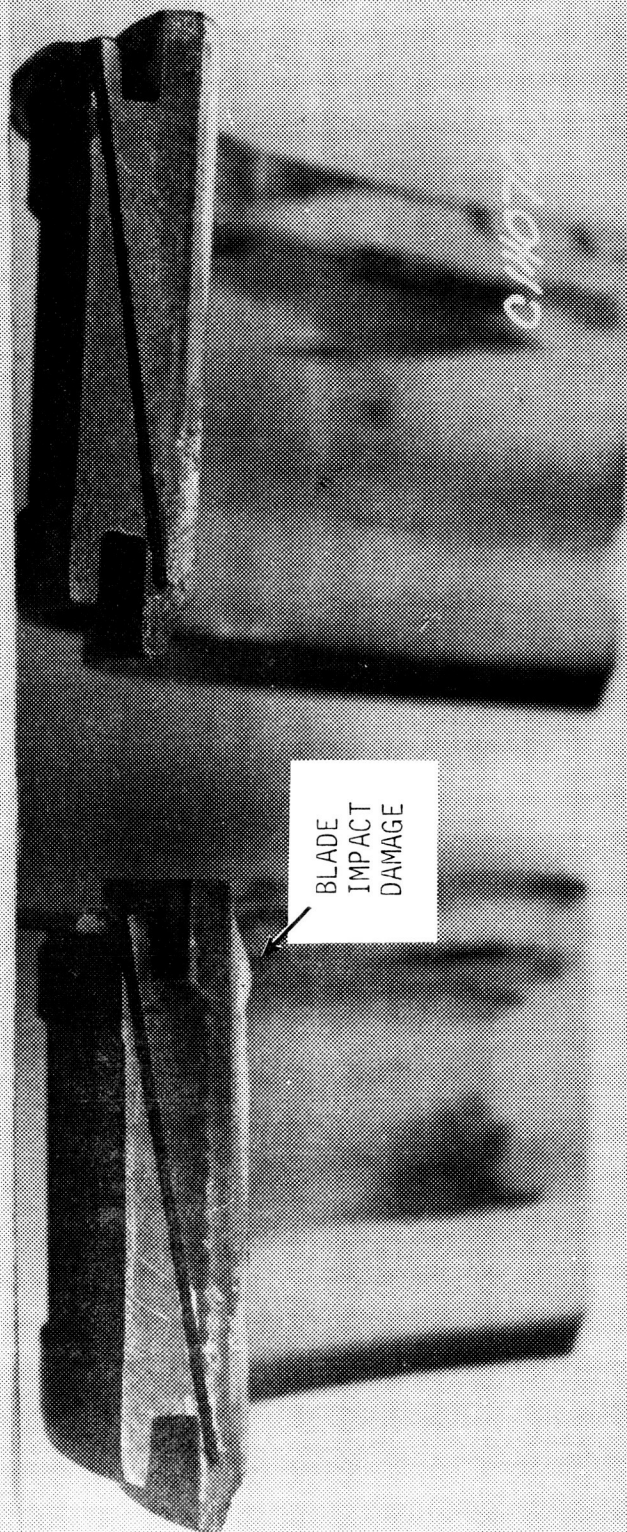


Figure 4-26. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #3 and #4 (Aft View).

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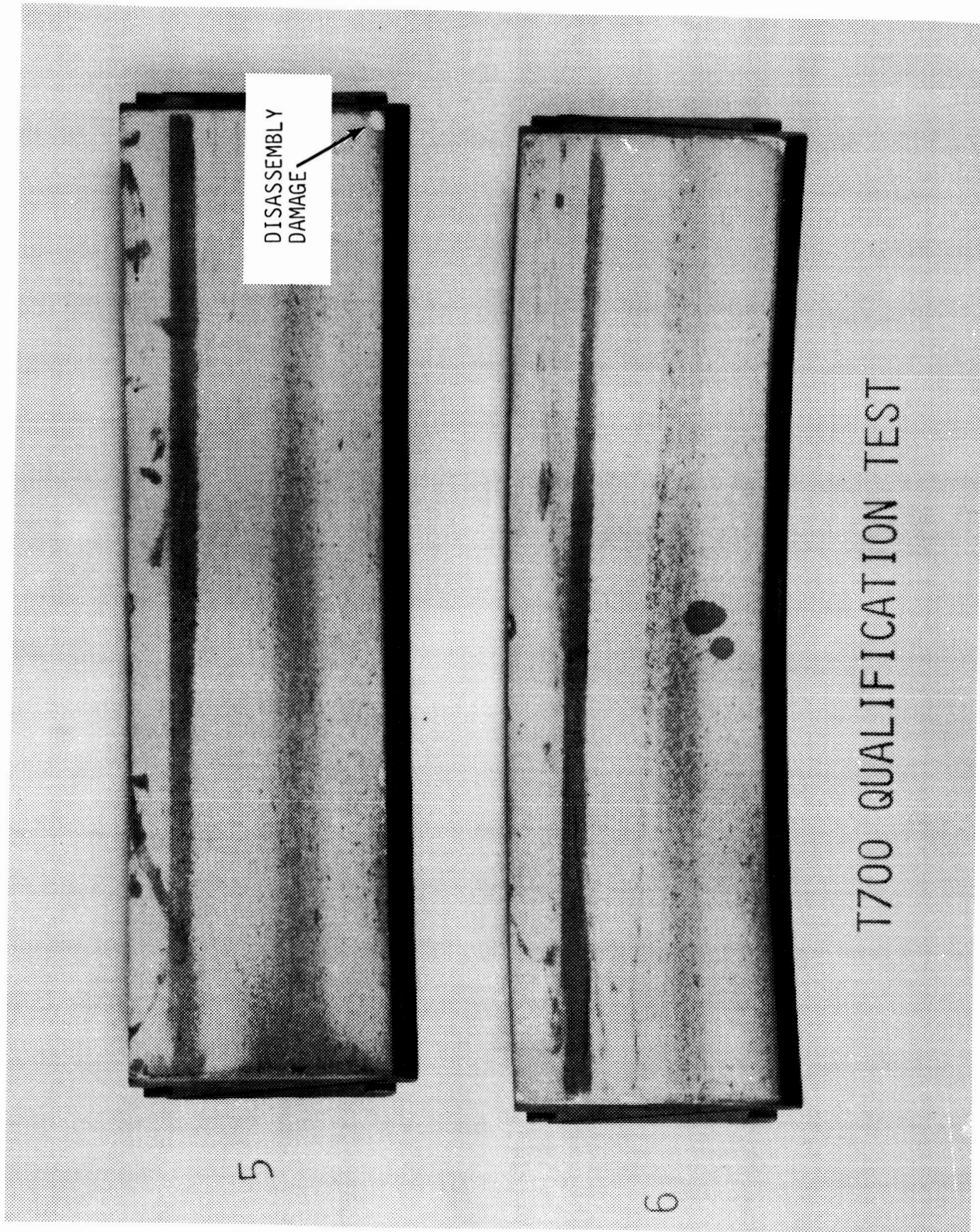
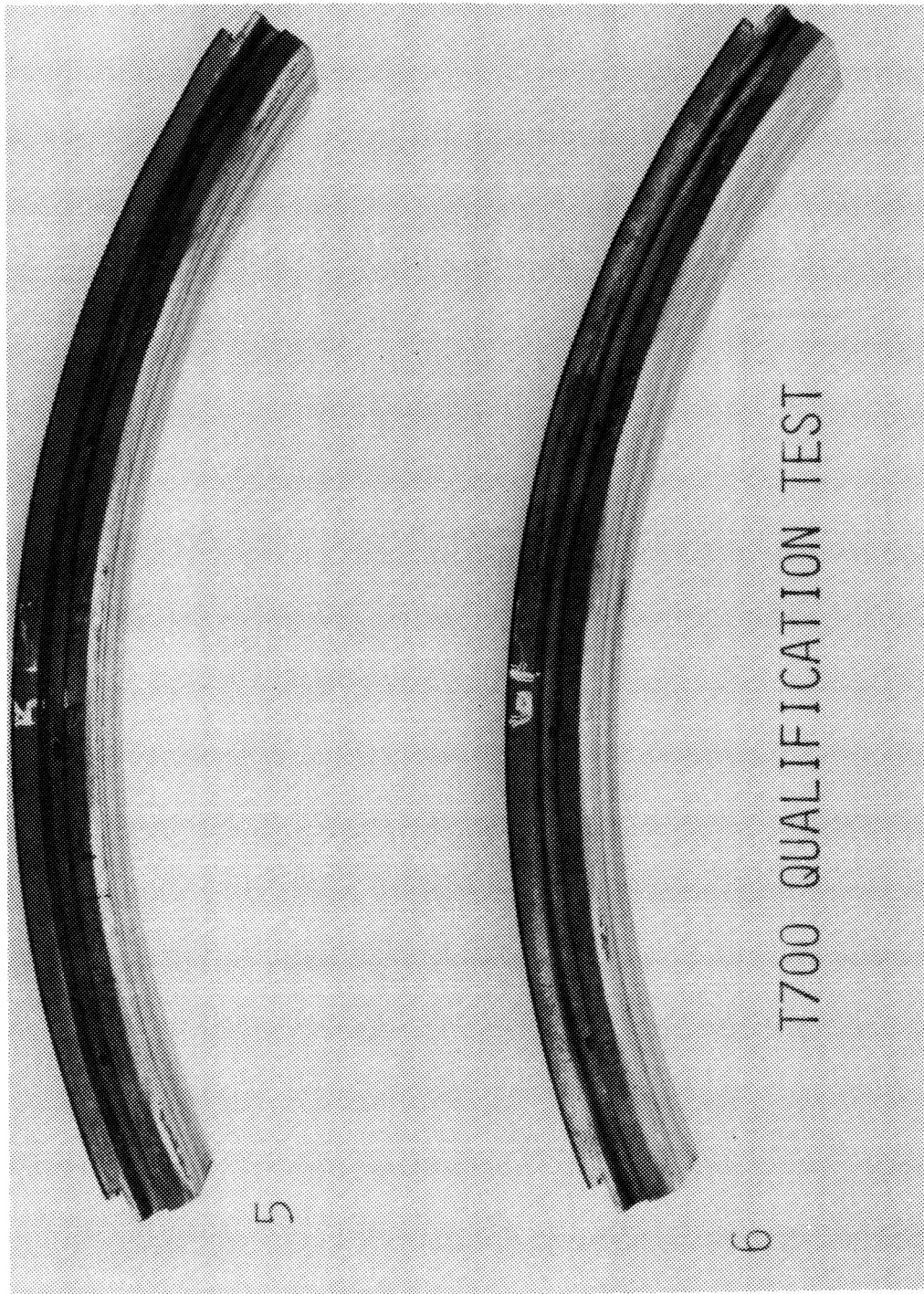


Figure 4-27. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #5 and #6.





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Figure 4-28. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #5 and #6 (End View).

# T700 QUALIFICATION TEST

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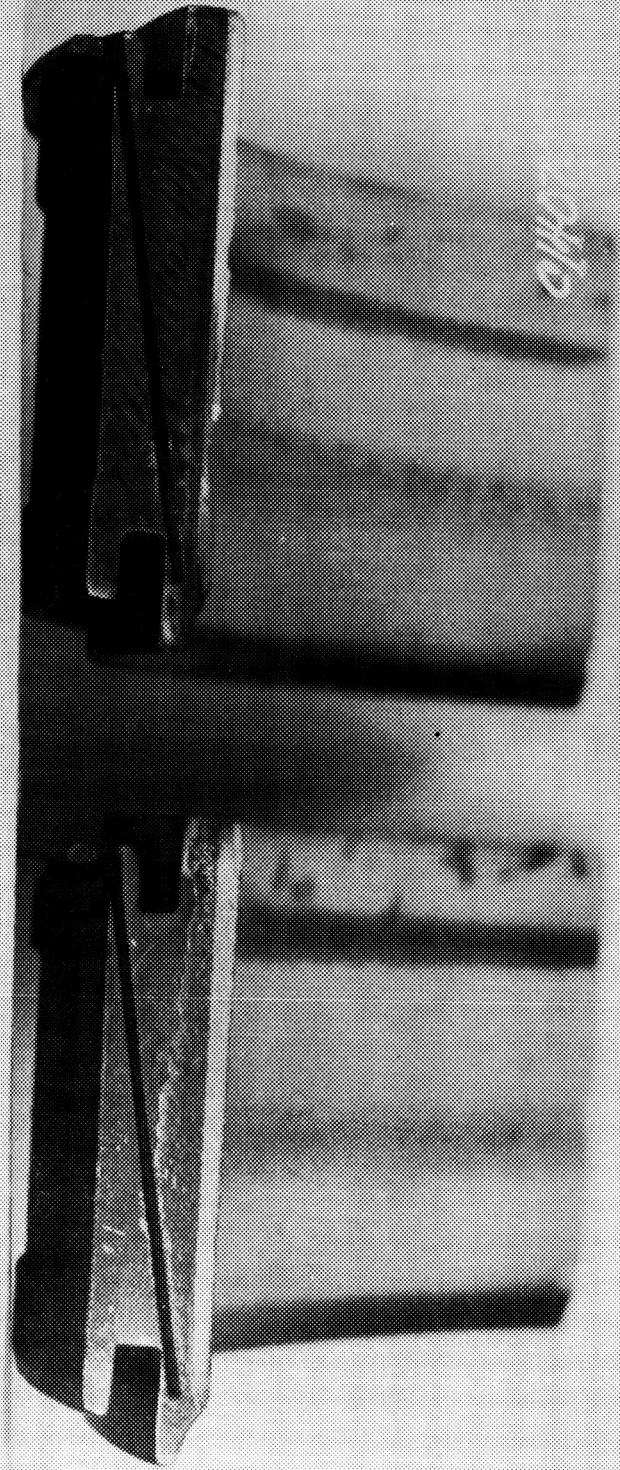
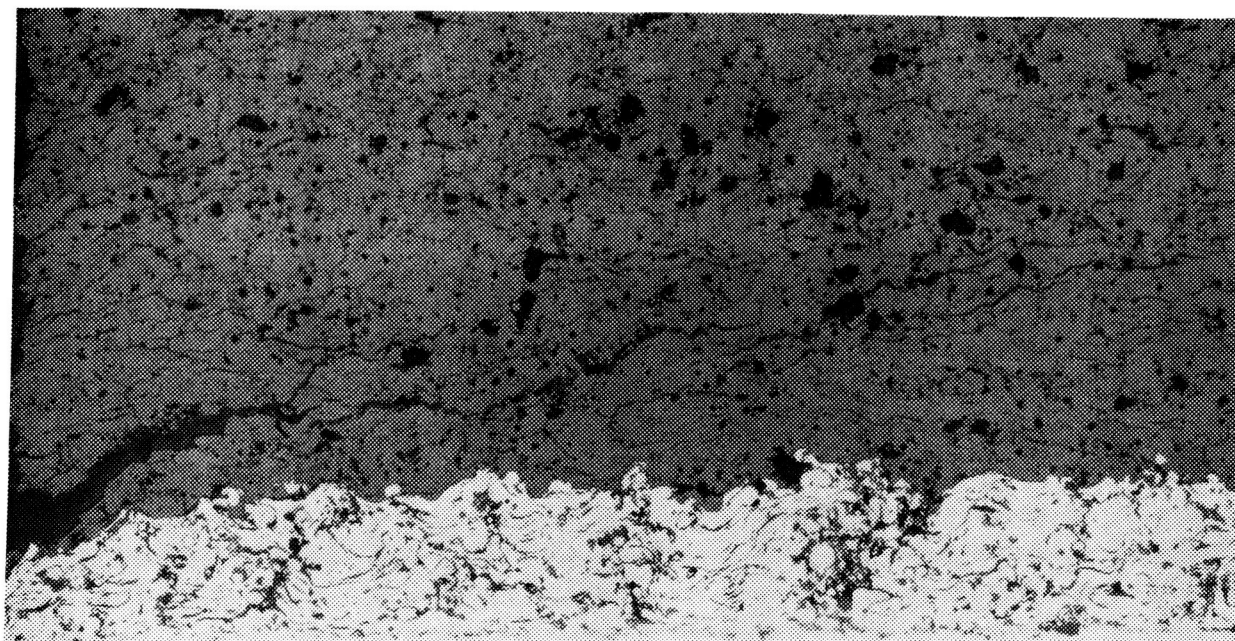


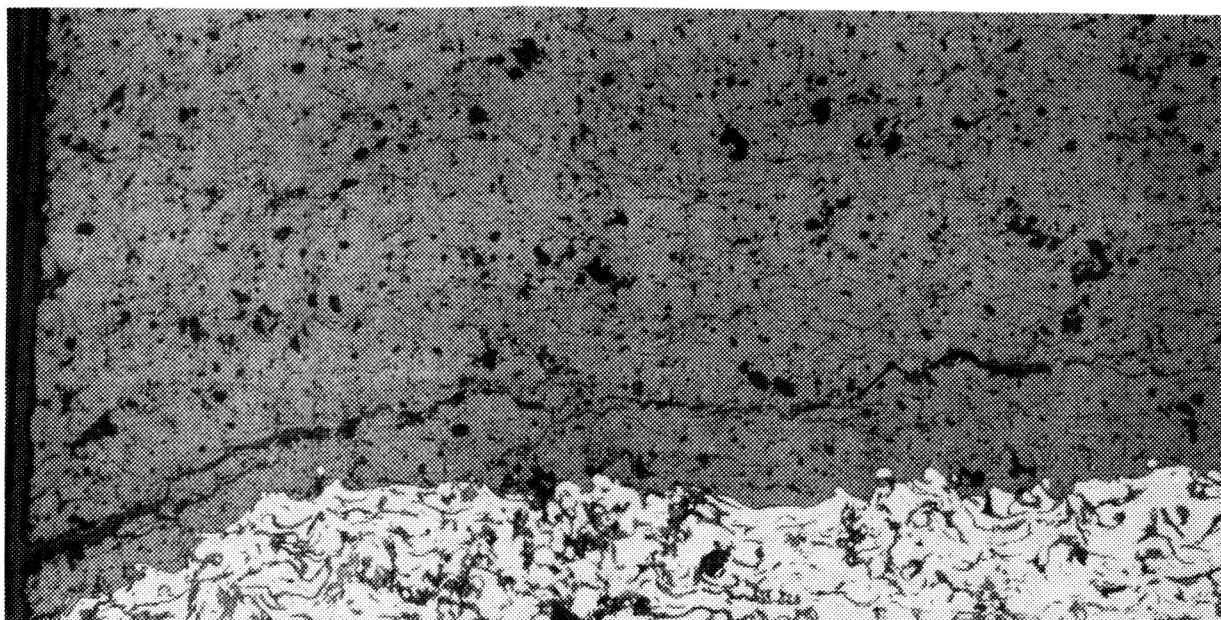
Figure 4-29. Ceramic Shrouds After Testing in Engine 372516-3 -  
GE-APS #5 and #6 (Aft View).





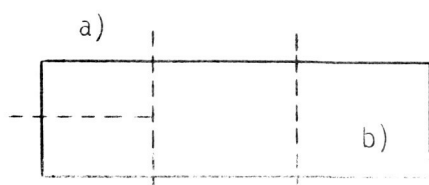
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b)

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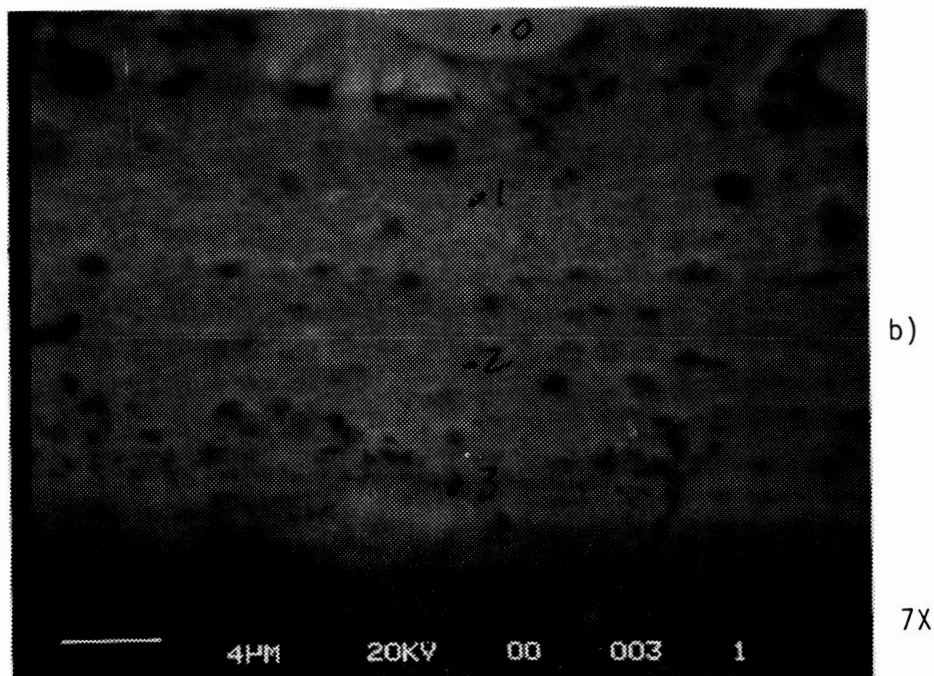
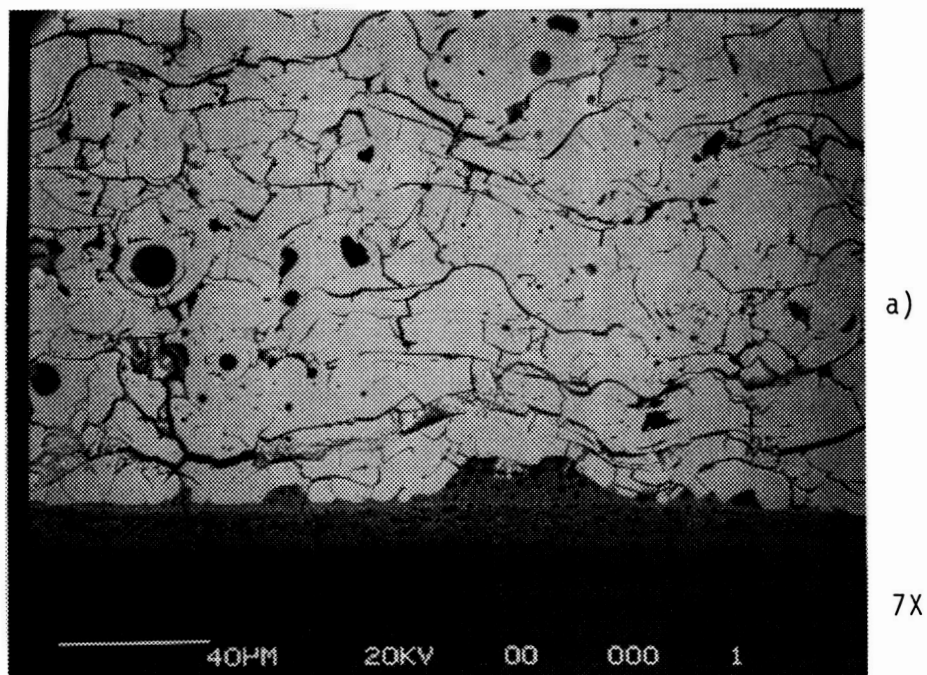


Schematic of Mount Locations

a) View Perpendicular to Shroud End

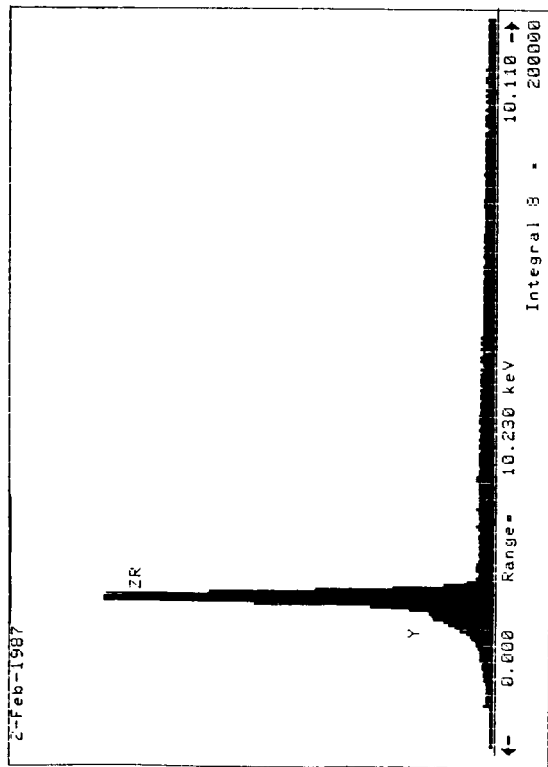
b) View Perpendicular to Trailing Edge

Figures 4-30a and b. Microstructure of GE-APS Shroud #2 (Engine 372516-3A)  
Showing Depth of Coating Cracks.

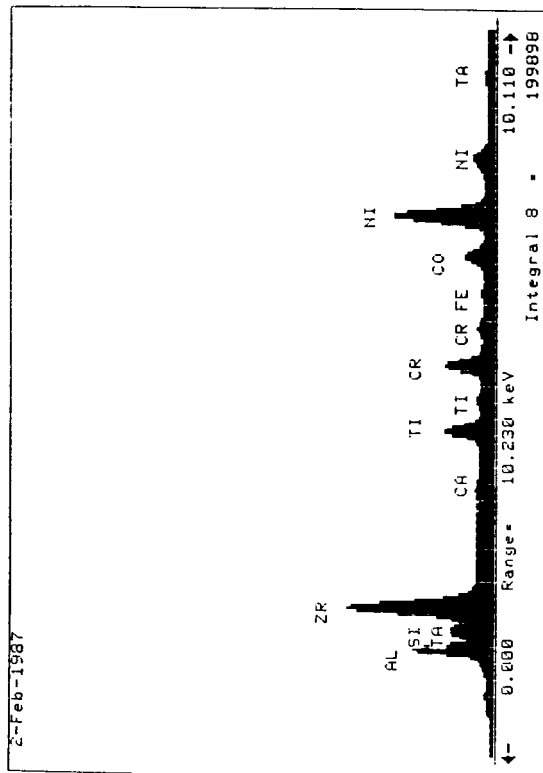


- a) Coating Cross Section
- b) Enlarged View of Rub Deposit Showing  
Locations Where EDAX Was Conducted

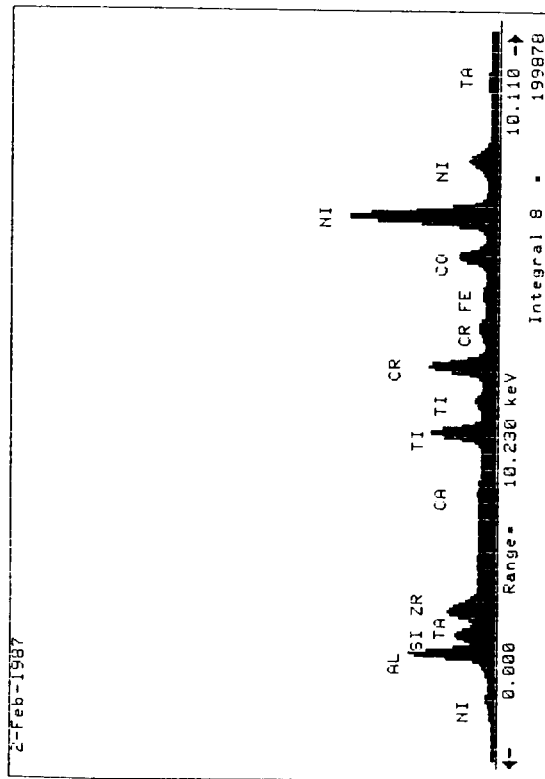
Figures 4-31a and b. SEM of Shroud Coating Showing Metal Deposit  
from Blade Rub.



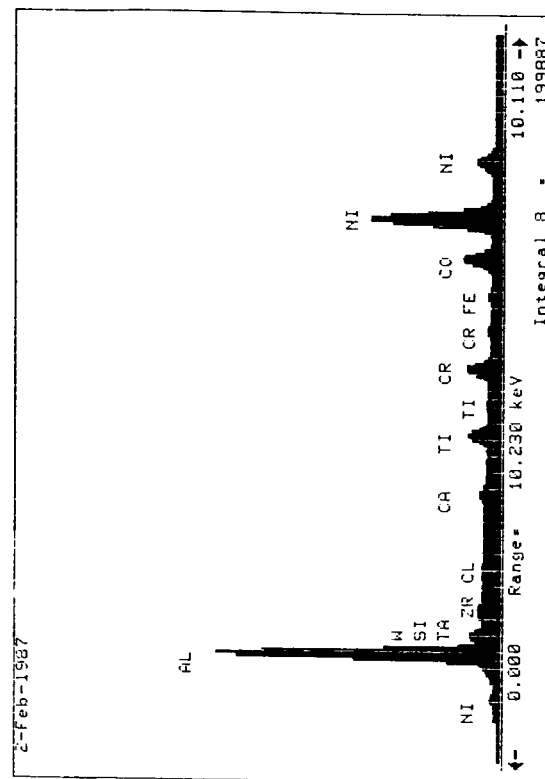
a) Point "0"



b) Point "1"



c) Point "2"



d) Point "3"

Figures 4-32a, b, c and d. EDAX Results of Rubbed Area Shown in Figure 31.

## Conclusions

This test:

- Was the most successful engine test of ceramic shrouds
- Showed production viability of ceramic shrouds
- Showed ceramic shroud resistance to turbine DOD (Stage 1 blade failure)
- Verified performance improvement of ceramic shrouds.

### 4.2.3 Sand Erosion Test

#### Engine 207018-8A

This 50-hour sand erosion test evaluated the erosion resistance of the ceramic shrouds as compared to the current production designs. The Stage 1 shrouds were a mixed configuration as shown in Figure 4-33. Stage 1 shrouds tested were: two solid shrouds, two Bradelloy shrouds and two ceramic shrouds (GE-APS) "P" quality.

This test consisted of dumping 80 lbs of sand into the inlet of the engine over a 50-hour period. The performance of the engine was measured at the start and completion of erosion testing. The performance of the engine was acceptable after sand erosion testing (test was a success).

The Stage 1 ceramic shrouds eroded more than the Bradelloy or solid shrouds, as shown in Figures 4-34 through 4-37, but did not erode through the ceramic coating. The average erosion depth of the Bradelloy shroud was negligible. The solid shroud eroded away about 9 mils average. The ceramic shroud eroded away about 21 mils average. The erosion path was mainly directly above the tip of the Stage 1 turbine blades. Erosion was considerably less above the trailing edge of the Stage 1 turbine blades where maintaining clearances is most critical. The ceramic shrouds are acceptable for continued engine operation.



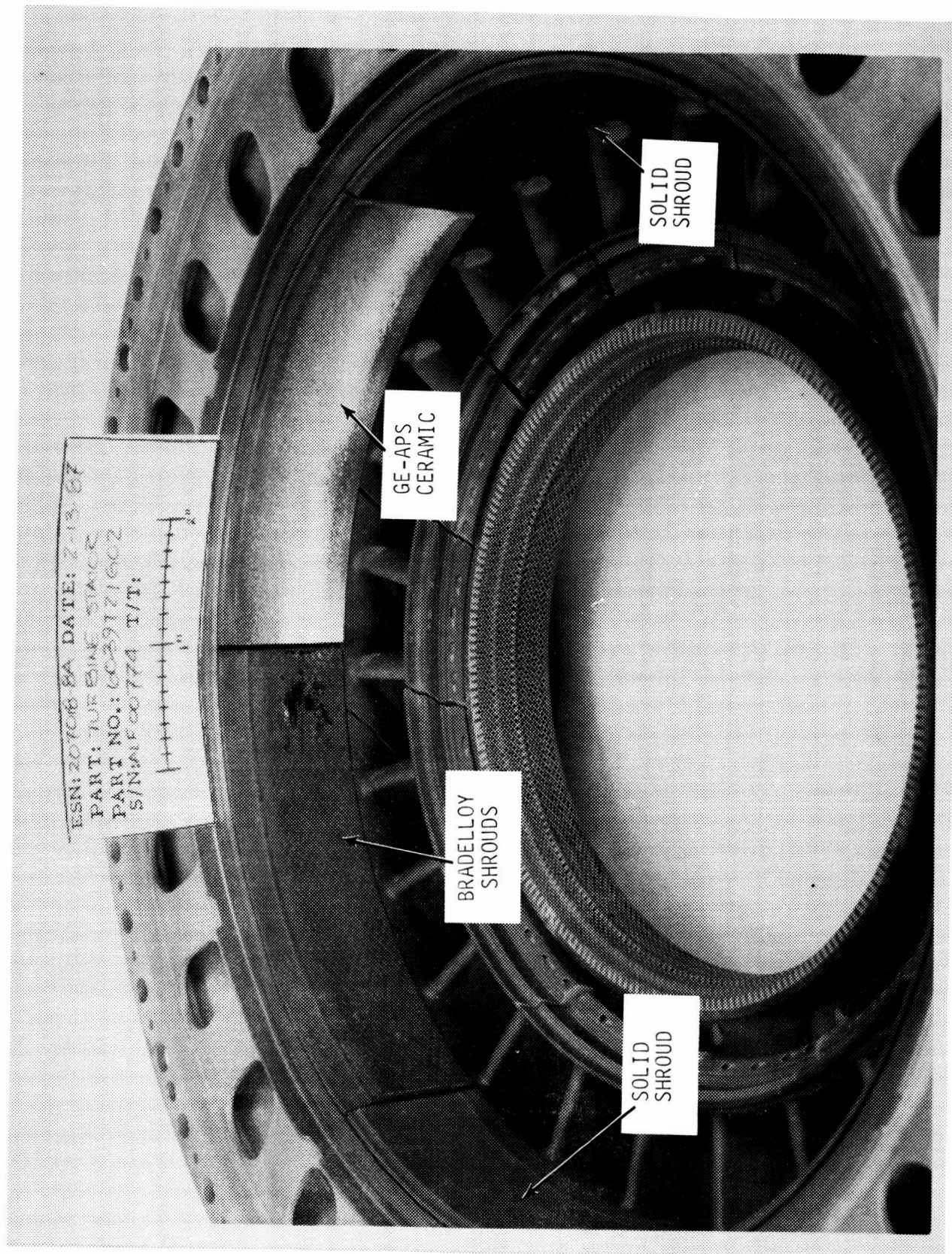


Figure 4-33. Ceramic Shrouds and Current Production Bradelloy and Solid Shrouds After Engine Test 207018-8A - View of GE-APS Installed in G6 Stator.

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MAIN EROSION ZONE  
DIRECTLY ABOVE STAGE 1 BLADE

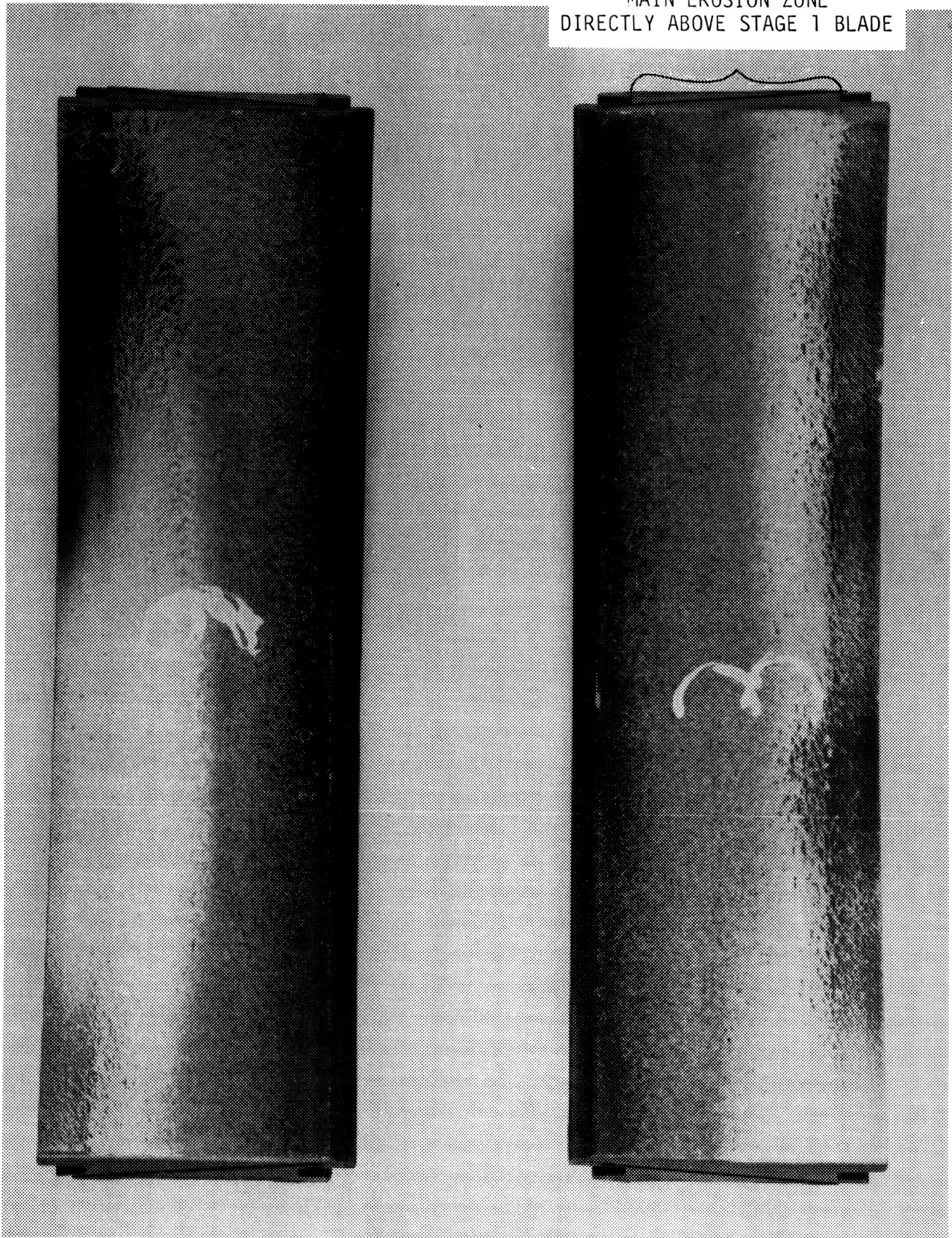


Figure 4-34. Engine 207018-8A GE APS Ceramic After Engine Test.





Figure 4-35. Engine 207018-8A Closeup of Erosion of Ceramic.

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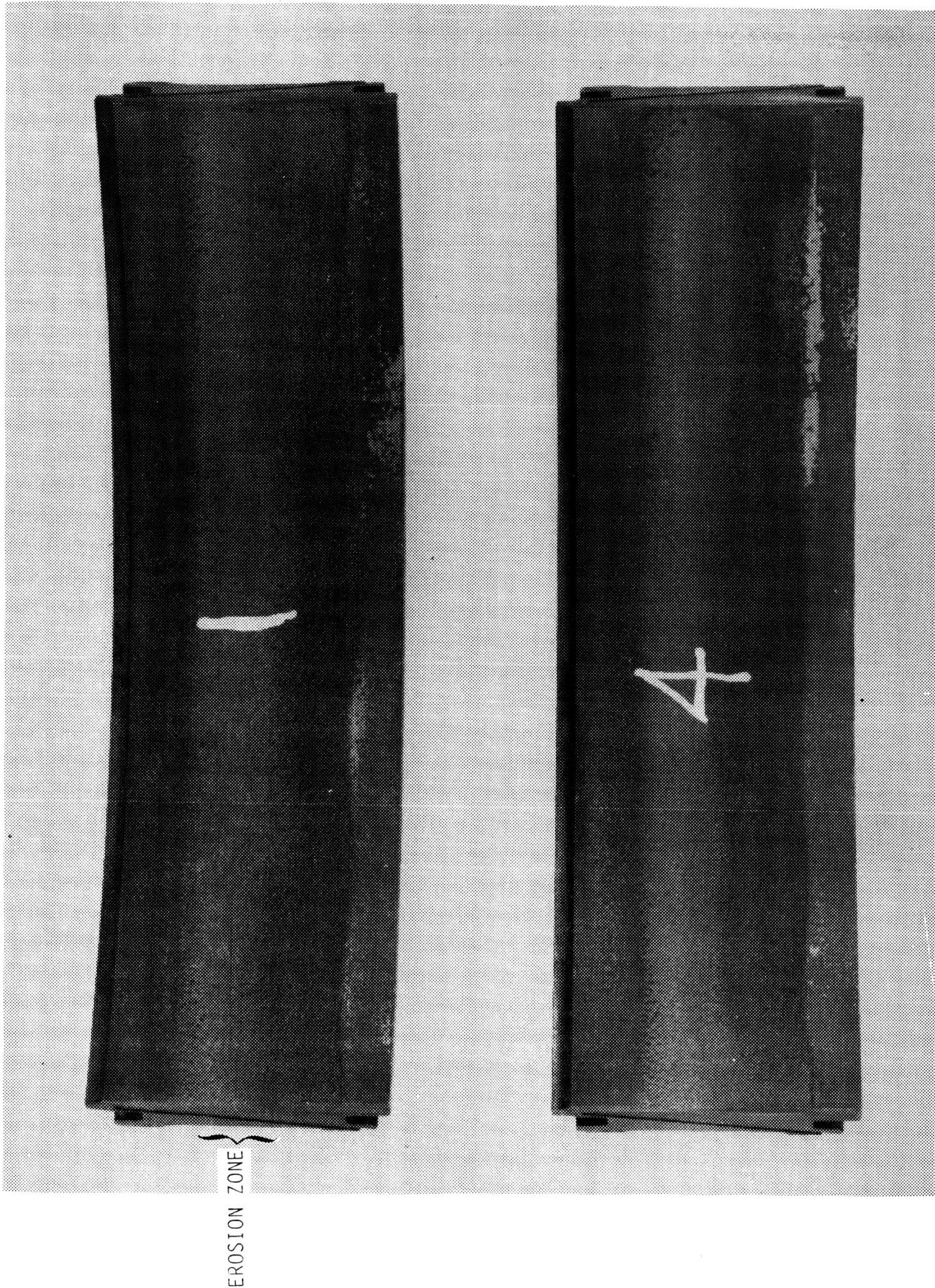


Figure 4-36. Engine 207018-8A Solid Shrouds After Engine Test.



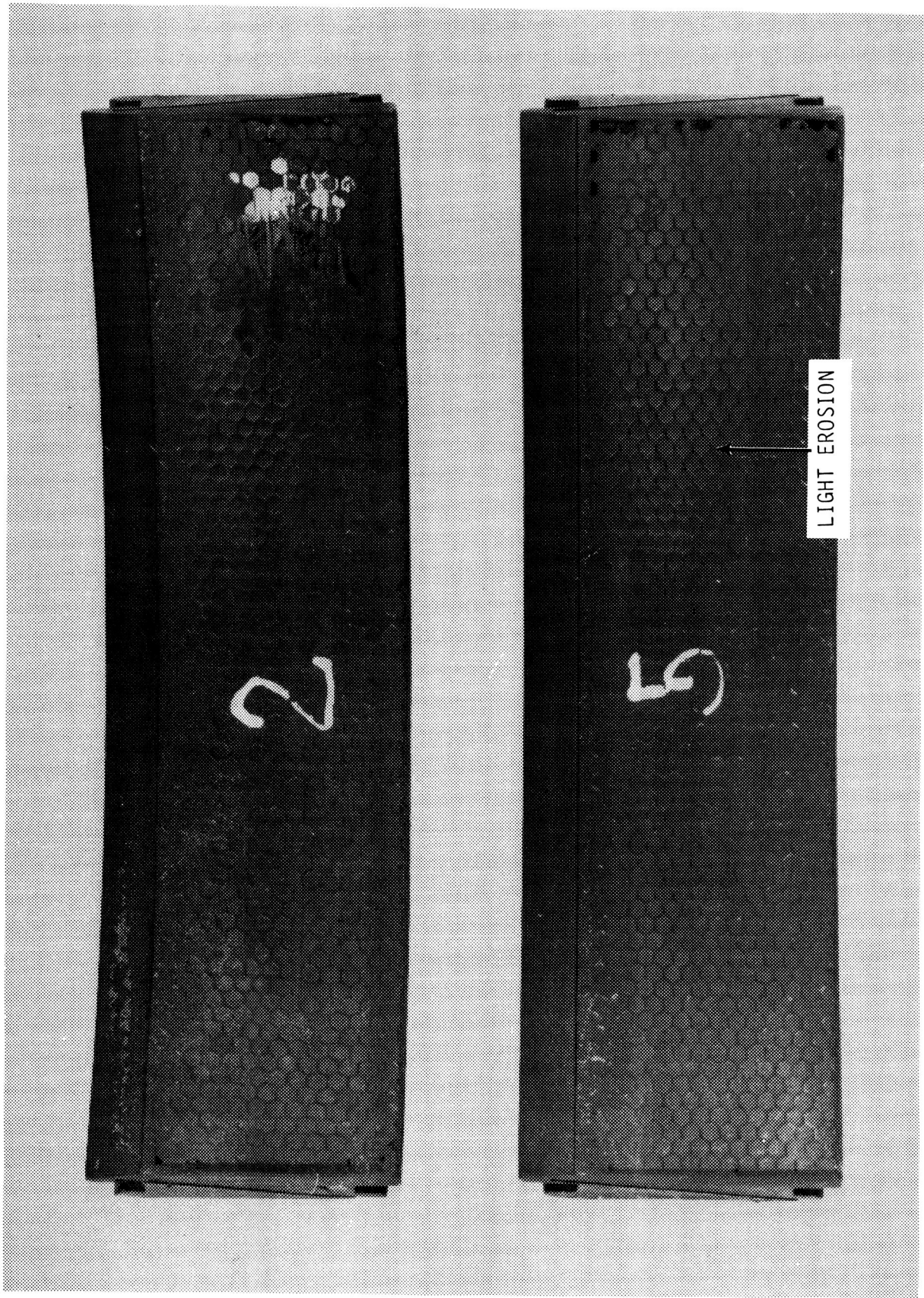


Figure 4-37. Engine 207018-8A Bradelloy Shrouds After Engine Test.

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## 5.0 CONCLUSIONS AND RECOMMENDATIONS

This final report summarizes and completes all technical work on the Army/NASA Contract NAS3-23174. Under the contract, General Electric successfully demonstrated the production viability of a Stage 1 high pressure turbine shroud with a ceramic-coated flowpath for the GE T700 turbine helicopter engine. This contract proved the performance, cost and durability benefits of the Stage 1 ceramic shroud over the current production shroud types, by extensive component and engine testing.

In light of the benefits demonstrated under this contract, it is recommended that the Stage 1 ceramic shrouds are substantiated for production introduction as soon as it is practical.



APPENDIX A  
CERAMIC SHROUD PROCESS SPECIFICATIONS

A.1 SCOPE

Acceptable quality of the ceramic shroud coating system is assured by the General Electric specifications as defined by the ceramic shroud drawing No. 6064T52.

A.2 NON-GOVERNMENT DOCUMENTS

Specifications

- |               |   |
|---------------|---|
| F50TF60-1(T)  | Plasma sprayed Yttria stabilized Zirconia coating (NiCrAlY bond coat)   |
| F50TF61-1(T)  | Plasma sprayed Yttria stabilized Zirconia coating (CoNiCrAlY bond coat) |
| A50TF239-1(T) | Zirconium oxide - Yttrium oxide powder (fine)                           |
| A50TF240-1(T) | Zirconium oxide - Yttrium oxide powder (chemically homogeneous)         |
| E50TF424-1(T) | Thermal shock Jets test method for ceramic coating                      |

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TEMPORARY SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the requirements specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until the "SI" issue is published.

PLASMA SPRAYED YTTRIA STABILIZED ZIRCONIA COATING  
 (Co-Ni-Cr-Al-Y BOND COAT)

1. SCOPE

1.1 Scope. This specification presents requirements for a two layered plasma sprayed coating consisting of a shielded arc plasma sprayed Co-Ni-Cr-Al-Y bond coat plus a Yttria stabilized Zirconia top coat used for ceramic shrouds.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified, the requirements herein apply to all classes.

CLASS A

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Capability - The words, "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

Coating Lot - All coated parts produced in a single production run from the same batch of raw materials under the same fixed conditions and submitted for inspection at one time.

Powder Lot - A quantity of powder produced from the same raw materials, blended, and and presented for inspection at one time.

Purchaser - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

PREPARED <i>Jim Johnson</i>	REVIEWED <i>W. H. Eber 3/28/86</i>	APPROVED BY:
APPROVED <i>Sam M. [unclear] 4/1/86</i>	DISTRIBUTION <i>10A</i>	<input checked="" type="checkbox"/> EVENDALE <input checked="" type="checkbox"/> LYNN

GT9020-7 (4-85)

GENERAL  ELECTRIC  
 CINCINNATI, OHIO 45215-6301

2.1 Issues of Documents. The following documents shall form a part of this specification to the extent specified herein. Unless otherwise specified, the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM B 328	Density and Interconnected Porosity of Sintered Powder Metal Structural Parts and Oil Impregnated Bearings (VOL. 02.05)
ASTM E 18	Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials (02.03, 03.01)

GENERAL ELECTRIC SPECIFICATIONS

A50TF239	Zirconium Oxide Yttrium Oxide Powder
E50TF424	Thermal Shock Jets Test Method for Ceramic Shrouds
E50TF121	Erosion Test Method For Compressor Clearance Control Coatings
B50TF195	Cobalt-Nickel-Chromium-Aluminum-Yttrium Alloy Thermal Spray Powder (CoNiCrAlY)
P1TF33	Preparation of Technical Plans for Coating Applications
P28TF2	Thermal Spray Operator and Equipment Qualification

GENERAL ELECTRIC PHOTOGRAPHS

8602012	Maximum Acceptable Porosity And Oxides At The Bond Coat/Substrate Interface.
8602013	Maximum Acceptable Porosity /Layer Lines In The bond Coat
8602014	Maximum Acceptable Porosity/Layer Lines In The Oxide Top Coat.
8602015	Maximum Acceptable Unmelted Particles In The Bond Coat

3. REQUIREMENTS

3.1 General

3.1.1 Technical Plan. A process technical plan shall be prepared for each part number in accordance with P1TF33, CL-A, and shall be submitted by the coating vendor and approved by the Purchaser prior to coating parts.

3.1.1.1 Multi-Surface Coverage Requirements. When coating is required on more than one continuous surface of a part, the process for each separate surface shall be included in the technical plan.

3.1.2 Equipment And Operator Qualification. The equipment and operators used in applying the coatings shall be qualified and the coating schedule certified in accordance with P28TF2, CL-A.

3.1.3 Surface Requirements. When coating is required on more than one surface of a part, property requirements for each separate surface shall conform to all requirements of this specification.

### 3.2 Coating Material.

3.2.1 Coating Materials. The coating materials shall be as follows:

#### Bond Coat

B50TF195 CL-A

#### Top Coat

A50TF239 CL-A

3.3 Powder Lot Qualification. Prior to the use of each new lot of powder for bond coat and top coat, test samples coated in accordance with the technical plan shall meet the requirements of this specification. Powder lots showing conformance shall be used for coating parts.

3.4 Coverage. The coating shall exhibit complete coverage in the areas specified for coating on the part drawing. There shall be no coating on areas other than those specified on the part drawing.

3.4.1 Surface Condition. The as-sprayed coating shall be uniform and free from cracks, blisters, chipping and flaking.

3.4.2 Adhesion. The coating shall exhibit no spalling or lifting.

### 3.5 Bond Coat

3.5.1 Bond Coat Thickness. The as-sprayed bond coat thickness shall be as specified on the part drawing.

3.5.2 Bond Coat/Substrate Porosity And Oxides. Porosity and oxides at the bond coat and substrate interface examined at 200X shall not exceed that of photograph 8602012

3.5.3 Bond Coat Porosity. Porosity in the bond coat examined at 200X shall not exceed that of photograph 8602013.

3.5.4 Bond Coat Layer Lines. Layer lines within the bond coat examined at 200X shall not exceed those of photograph 8602013.

3.5.5 Unmelted Particles (Bond Coat). Unmelted particles within the bond coat examined at 200X shall not exceed those of photograph 8602015.

### 3.6 Top Coat

F50TF61-1(T)

3.6.1 Top Coat Thickness Tolerance. The as-sprayed top coat thickness for parts and test panels shall not exceed +0.010", -0.000" of the thickness requirements specified on the drawing.

3.6.2 Top Coat Porosity. Porosity in the oxide top coat examined at 200X shall not exceed that of photograph 8602014.

3.6.3 Top Coat Layer Lines. Layer lines within the oxide top coat examined at 200X shall not exceed those of photograph 8602014.

3.6.4 Top Coat Density. The density of the free standing oxide layer when determined per ASTM B 328 shall be between 5.39 to 5.63 grams per cubic centimeter.

3.6.4.1 Density Panel Preparation. The density test panel may be processed with or without bond coat and a minimum of panel surface preparation.

3.6.4.2 Oxide Removal. The oxide layer may be removed from the metallic substrate by thermal shock or chemical strip.

3.6.5 Top Coat Erosion. Erosion test will be performed on a minimum of one (1) panel in accordance with E50TF121 CL-A. Erosion factors (E#) shall be within the following limits:

E#	14.0 - 20.0 Sec/Mil
----	---------------------

3.6.7 Top Coat Surface Hardness. The Rockwell 15N hardness of the top coat surface shall have an average value of 85 minimum.

3.7 Metallographic Requirements. Metallographic evaluations shall be performed on heat treated and aged (as specified on the drawing) samples prepared for evaluation by a method approved by the purchaser.

3.8 Thermal Shock Resistance Requirements. Each coating lot of parts shall meet the following thermal shock requirements:

(a) Test buttons processed with each coating lot shall:

- (1) Not exhibit a combined crack length between the bond coat and the top coat or within the top coat in excess of 50% of the button circumference.
- (2) Exhibit no spallation of the top coat.
- (3) Exhibit no separation between the bond coat and the substrate.
- (4) Exhibit no extension of surface cracking down into linear circumferential cracking.



**3.9 Recoating.** Parts rejected because of discrepant coating shall have the coating stripped by a method approved by the Purchaser and shall be recoated in accordance with all of the requirements of this specification.

**3.9.1 Recoated Parts.** A part shall not be stripped and recoated more than twice. Stripped and recoated parts shall be identified on the certificate of test.

**3.10 Test Specimens.** Test specimens shall be processed with each coating lot and shall be placed in the same plane at the average distance from the spray nozzle as the surfaces being coated. The number and type shall meet the requirements of Table I.

TABLE I - Test Specimens (Minimum Quantity)

<u>QUANTITY</u>	<u>CONFIGURATION</u>	<u>MATERIAL</u>	<u>PURPOSE</u>
2	0.125" + 0.005"x1.0" Dia.	Identical to parts	JETS test
1	0.065" to 0.125"x1.0"x2.0" Panel	Approved by Purchaser	Erosion Test
1	0.065" to 0.125"x2.0"x2.0" Panel	Approved by Purchaser	Density
1	0.065" to 0.125"x0.625"x1.0" Panel	Approved by Purchaser	Metallography

**3.11 Certificate of Test.** The coating vendor shall furnish a certificate of test with each lot of coated parts. The certificate shall include the numerical results of all required tests and inspections and shall show that the results are in accordance with the requirements of this specification. Parts which have been reworked shall be identified. The certificate shall be mailed by the coating vendor to the Purchaser with or preceding the shipment of parts. The certificate of test shall also contain the following information.

- (a) Purchase order number
- (b) Part drawing number
- (c) Quantity of parts
- (d) This GE specification number, class and revision number
- (e) Powder manufacturer's name and powder lot number

#### 4. QUALITY ASSURANCE PROVISIONS

**4.1 General.** Coated parts shall be tested in accordance with a quality plan approved by the Purchaser to determine conformance with the requirements of this specification. The vendor quality plan shall include a minimum of three coating runs demonstrating acceptable coating characteristics on actual hardware along with test specimens from Table I. The test specimens from Table I will then be used for accepting subsequent coating runs.

F50TF61-1(T)

4.2 Powder Lot Qualification. Each new lot of powder for bond coat and top coat shall be demonstrated capable of conforming to the requirements of this specification prior to coating parts.

4.3 Visual Inspection. Visual inspection of each coated surface shall be performed at 50X magnification.

4.4 Coating Thickness Determination. Thickness shall be determined at a minimum of three different locations on a coated part or flat test sample using flat anvil micrometer measurements. Flat test samples shall be of a material having a similar composition and hardness, prepared for coating in the same manner and positioned to received the same spray deposit as the part being sprayed. Other methods may be used if approved by the Purchaser.

4.5 Metallographic Evaluation. The vendor shall perform a metallographic evaluation on one (1) test panel from Table I at 200X magnification.

4.6 Density Determination. Density of the free standing oxide layer shall be determined in accordance with ASTM B 328.

4.7 Erosion Test. The erosion test shall be performed in accordance with E50TF121 CL-A

4.8 Surface Hardness. The top coat surface hardness test shall be performed in accordance with ASTM E 18 on all quality control specimens using a superficial hardness tester.

4.8.1 Equipment Calibration. Hardness tester calibration shall be confirmed on standard block prior to each coating lot evaluation.

4.9 Thermal Shock Test. Thermal shock resistance shall be determined on a TS JETS tester in accordance with E50TF424 at an oxide thickness and surface temperature to be determined by the Purchaser.

5. PACKAGING

5.1 Packing. Coated parts shall be suitably packed to prevent damage or loss in shipment.

5.2 Marking. Each shipment shall be legibly marked with the purchase order number coating vendor's name, GE part designation, number of parts, this GE specification, class and revision number.

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AIRCRAFT ENGINE BUSINESS GROUP  
*Specification*

SPECIFICATION NO. A50TF239  
ISSUE NO. 1(T)  
DATE March 10, 1986  
PAGE 1 OF 3  
FSCM 07482  
SUPERSEDES New

TEMPORARY SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the requirements specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until the "SI" issue is published.

ZIRCONIUM OXIDE-YTTRIUM OXIDE POWDER  
(Fine)

1. SCOPE

1.1 Scope. This specification presents requirements for a zirconium oxide-yttrium oxide powder suitable for thermal spraying.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified, the requirements herein apply to all classes.

CLASS A:

1.2 Definitions. For purposes of this specification, the following definitions shall apply.

**Purchaser** - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

**Capability** - The words, "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

**Powder Lot** - A quantity of powder produced from the same raw materials, blended, and presented for inspection at one time.

2. APPLICABLE DOCUMENTS

2.1 Issues of Documents. The following documents shall form a part of this specification to the extent specified herein. Unless otherwise specified, the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM B 214 Method of Subsieve Analysis of Granular Metal Powders

PREPARED <i>gm Johnson</i>	REVIEWED <i>W.H. Lee</i> 2/24/86	APPROVED BY:
APPROVED <i>Sam H. Lee</i> 2/24/86	DISTRIBUTION <i>10A</i>	<input checked="" type="checkbox"/> EVENDALE <input checked="" type="checkbox"/> LYNN

GT9020-7 (4-85)

GENERAL ELECTRIC  
CINCINNATI, OHIO 45215-6301

### 3. REQUIREMENTS

3.1 Chemical Composition, Weight Percent. Powder supplied to this specification shall have the following composition:

Yttrium Oxide ---	6.00-8.00	CaO -----	0.5 Max.
Al <sub>2</sub> O <sub>3</sub> -----	0.7 Max.	MgO -----	0.3 Max.
SiO <sub>2</sub> -----	1.5 Max.	Zirconium Oxide -----	Balance
TiO <sub>2</sub> -----	0.5 Max.	Total All Others -----	1.5 Max.
Fe <sub>2</sub> O <sub>3</sub> -----	0.5 Max.		

3.1.2 Powder Chemical Analysis. The analysis made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of 3.1 and shall be reported in the certificate of test herein specified.

3.2 Quality. The powder shall be uniform in color, quality, and condition. It shall be dry and free from foreign materials and from imperfections detrimental to its sprayability.

3.3 Manufacturing Processes. The material vendor shall use the same ingredients and manufacturing processes for production material supplied to this specification as for approved sample material. If necessary to make any changes in ingredients or processing, the vendor shall obtain permission from the Purchaser prior to incorporating such change.

3.4 Particle Size. Powder shall conform to the particle size requirements of Table I and Table II..

Table I - Particle Size

Component	ASTM (U.S. Standard Sieve Designation)	Weight Percent
Zirconia-Yttria Powder	+200	0.1% Max.
	-200 +230	10.1% Max.
	-325	55-85%

3.4.1 Subsieve Particle Analysis. Powder passing through the number 325 screen shall conform to sub sieve particle requirements of Table II.

Table II Subsieve Particle Size

Component	Microtrac Designation	Weight Percent
Zirconia-Yttria Powder	-22 Micrometer	16% Max.
	-11 Micrometer	5% Max.
	-5.5 Micrometer	0

3.5 Sprayability Test. Powder shall be capable of producing thermal sprayed coatings which are smooth, uniform and free from lumps .

#### 4. QUALITY ASSURANCE

4.1 Certificate of Test. A certificate of test on each shipment of material supplied to this specification shall be submitted by the manufacturer and mailed with or preceding the shipment of material. This certificate shall give the numerical results of all required tests and shall show that the results are in accordance with the requirements of this specification. The certificate shall also show the purchase order number, vendor's designation and lot number, quantity, and this GE specification number, class, and revision number.

4.2 Chemical Analysis. Chemical analysis shall be conducted in accordance with standard ASTM methods or by methods agreed upon by the Purchaser and Vendor.

4.3 Sieve Analysis. Sieve analysis shall be conducted in accordance with ASTM B 214.

4.3.1 Subsieve Analysis. Particle analysis shall be conducted using Microtrac or a method agreed upon between the Purchaser and vendor.

4.4 Sprayability Test. The sprayed coating shall be capable of meeting the requirements of 3.5 when the powder is sprayed with commercially available production type equipment. Spraying shall be performed in accordance with the equipment manufacturer's recommended practices and spraying parameters.

#### 5. PACKAGING

5.1 Packaging. Material shall be adequately packed in sealed contamination free and moisture-proof containers.

5.2 Marking. Each package shall be legibly marked with the purchase order number, manufacturer's name, quantity, batch or lot number and this GE specification number, class and revision number.



AIRCRAFT ENGINE BUSINESS GROUP  
*Specification*

SPECIFICATION NO. A50TF240  
ISSUE NO. 1(T)  
DATE March 10, 1986  
PAGE 1 OF 4  
FSCM 07482  
SUPERSEDES New

TEMPORARY SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the requirements specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until the "SI" issue is published.

ZIRCONIUM OXIDE-YTTRIUM OXIDE POWDER  
(Chemically Homogeneous)

1. SCOPE

1.1 Scope. This specification presents requirements for a zirconium oxide-yttrium oxide powder suitable for thermal spraying.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified, the requirements herein apply to all classes.

CLASS A: 8 Percent  $Y_2O_3$  -  $ZrO_2$   
CLASS B: 7 Percent  $Y_2O_3$  -  $ZrO_2$   
CLASS C: 6 Percent  $Y_2O_3$  -  $ZrO_2$

1.2 Definitions. For purposes of this specification, the following definitions shall apply.

**Purchaser** - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

**Capability** - The words, "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

**Chemically Homogeneous** - Uniform in chemical composition throughout.

**Powder Lot** - A quantity of powder produced from the same raw materials, blended, and presented for inspection at one time.

PREPARED <i>Jim Johnson</i>	REVIEWED <i>W. H. Nelson</i> 2/28/86	APPROVED BY:
APPROVED <i>Steve M. [illegible]</i> 2/28/86	DISTRIBUTION 10A	<input checked="" type="checkbox"/> EVENDALE <input checked="" type="checkbox"/> LYNN

GT9020-7 (4-85)

GENERAL  ELECTRIC  
CINCINNATI, OHIO 45215-6301

## APPLICABLE DOCUMENTS

2.1 Issues of Documents. The following documents shall form a part of this specification to the extent specified herein. Unless otherwise specified, the latest revision shall apply.

## AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM C 819      Specific Surface Area of Carbon or Graphite

## 3. REQUIREMENTS

3.1 Material Source. Material shall be procured only from sources approved by the Purchaser.

3.2 Chemical Composition, Weight Percent. Powder supplied to this specification shall have the following composition:

	CLASS A	CLASS B	CLASS C
Yttrium Oxide ---	7.0-9.0	6.0-8.0	5.0-7.0
Al <sub>2</sub> O <sub>3</sub> -----	0.2 Max.	0.2 Max.	0.5 Max.
SiO <sub>2</sub> -----	1.0 Max.	1.0 Max.	1.5 Max.
TiO <sub>2</sub> -----	0.5 Max.	0.5 Max.	0.5 Max.
Fe <sub>2</sub> O <sub>3</sub> -----	0.5 Max.	0.5 Max.	0.5 Max.
HfO <sub>2</sub> -----	2.5 Max.	2.5 Max.	2.5 Max.
Other Oxides -----	1.5 Max.	1.5 Max.	1.5 Max.
Zirconium Oxide ---	Balance	Balance	Balance

3.2.1 Powder Chemical Analysis. The analysis made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of 3.2 and shall be reported in the certificate of test herein specified.

3.3 Manufacture. The powder shall be chemically homogeneous, formed by either solid state sintering or fusion, uniform in color, quality, and condition. It shall be dry and free from foreign materials and from imperfections detrimental to its sprayability.

3.4 Particle Size Analysis. Powder shall conform to the particle size requirements of Table I.

Table I - Microtrac Analysis Limits

Percentile Finer	Particle Diameter (Microns)	
	Minimum	Maximum
10th Percentile (PS)	42	49
50th Percentile (PM)	68	77
90th Percentile (PH)	107	121

3.5 Specific Surface Area. Powder shall have a specific surface area of 0.1 to 0.4 m<sup>2</sup>/g.

3.6 Sprayability Test. Powder shall be capable of producing thermal sprayed coatings which are smooth, uniform, and free from lumps.

3.7 Certificate of Test. A certificate of test on each shipment of material supplied to this specification shall be submitted by the manufacturer and mailed with or preceding the shipment of material. This certificate shall give the numerical results of all required tests and shall show that the results are in accordance with the requirements of this specification. The certificate shall also show the purchase order number, vendor's designation and lot number, quantity, and this GE specification number, class, and revision number.

#### 4. QUALITY ASSURANCE PROVISIONS

4.1 The material vendor shall use the same ingredients and manufacturing processes for production material supplied to this specification as for approved sample material. If necessary to make any changes in ingredients or processing, the vendor shall obtain permission from the Purchaser prior to incorporating such change.

4.2 Chemical Analysis. Chemical analyses shall be conducted in accordance with standard ASTM methods or by methods agreed upon by the Purchaser and vendor.

4.3 Particle Size Analysis. Particle size distribution shall be determined by Microtrac analysis.

4.4 Specific Surface Area Measurement. The powder shall be capable of meeting the requirements of 3.5 when its specific surface area is measured in accordance with ASTM C 819.

4.5 Sprayability Test. The sprayed coating shall be capable of meeting the requirements of 3.6 when the powder is sprayed with commercially available production type plasma spray equipment. Spraying shall be performed in accordance with the equipment manufacturer's recommended practices and spraying parameters.

#### 5. PACKAGING

5.1 Packaging. Material shall be adequately packed in sealed contamination free and moisture-proof containers.

A50TF240-1(T)

5.2 Marking. Each package shall be legibly marked with the purchase order number, manufacturer's name, quantity, batch or lot number and this GE specification number, class and revision number.

6. NOTES

6.1 Data for Ordering. The Data for Ordering Sheet below is listed for information purposes only.

DF0-A50TFJG	Zirconium Oxide - Yttrium Oxide Power (Chemically Homogeneous)
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AIRCRAFT ENGINE BUSINESS GROUP  
*Specification*

SPECIFICATION NO. E50TF424  
ISSUE NO. 1(T)  
DATE March 10, 1986  
PAGE 1 OF 3  
FSCM 07482  
SUPERSEDES NEW

TEMPORARY SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the requirements specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until the "S1" issue is published.

THERMAL SHOCK JETS TEST METHOD  
FOR CERAMIC COATINGS

1. SCOPE

1.1 Scope. This specification describes a method for determining the thermal shock characteristics of ceramic shrouds.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified, the requirements herein apply to all classes.

CLASS A

1.2 Definitions. For purposes of this specification, the following definitions shall apply.

Purchaser - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

Crack - A linear discontinuity having a length of four times its width or greater.

2. APPLICABLE DOCUMENTS

2.1 Issues of Documents. There are no applicable documents.

PREPARED <i>Jim Johnson</i>	REVIEWED <i>W A Nelson 2/28/86</i>	APPROVED BY:
APPROVED <i>Sam Martorello 2/22/86</i>	DISTRIBUTION <i>55</i>	<input checked="" type="checkbox"/> EVENDALE <input type="checkbox"/> LYNN

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GENERAL  ELECTRIC  
CINCINNATI, OHIO 45215-6301

## 3. GENERAL REQUIREMENTS

3.1 Equipment Unless otherwise agreed upon between Purchaser and Vendor testing equipment and parameters shall be as follows:

- (a) Test Facility - consisting of a heat source utilizing hot gasses and cooling source using filtered shop air, each able to deliver a concentrated flow .
- (b) Holder - Device able to hold the test samples rigid while withstanding temperatures up to a maximum of 2800°F (1530°C)
- (c) Heat Source - Gas capable of producing a sample temperature of 2800°F (1530°C)
- (d) Cooling Source - Filtered shop air.
- (e) Indexing System - Automatic equipment capable of sequencing specimens through repeated cycles of heating and cooling.
- (f) Temperature Controls - Optical pyrometer capable of a reading temperatures up to 2800°F (1530°C) with an accuracy of  $\pm 20^\circ\text{F}$  ( $\pm 7^\circ\text{C}$ ).

## 4. THERMAL SHOCK TEST

4.1 Uncoated Test Buttons. Test buttons shall be  $0.125 \pm 0.010$  inch ( $6.35 \pm 0.250$  mm) thick and  $1.0 \pm 0.020$  inch ( $25.4 \pm 0.50$  mm) in diameter.

4.1.1 Coating Thickness. Ceramic and bond coating thickness shall be the same as that of the coating thickness of the part represented.

4.2 Button Preparation. Remove all overspray from the entire circumference of all test buttons. Removal shall be accomplished by polishing with a maximum grit size of 150.

4.2.1 Button Circumference. Measure the exact circumference of the polished button at the bond line between the oxide coating and the bond coat.

4.3 Testing. Testing shall be done after calibration of the test equipment and shall be as follows:

4.4 Test Conditions. One test cycle shall consist of a 20 second exposure to the heat followed immediately by a 20 second cool.

4.4.1 Test Temperatures. The heating and cooling temperatures for front and back side shall be agreed upon between the Purchaser and vendor.

4.5 Test Duration. Buttons shall be exposed to 2000 test cycles.

4.5.1 Alternate Procedure. Changes in the equipment or processing, once established, shall not be changed without prior approval of the Purchaser.



## 5. EVALUATION

5.1 Examination. The entire periphery shall be examined visually at a magnification of 50X.

5.1.1 Cracking. The length of all linear discontinuities exceeding 0.005 X 0.020 inch (0.130 + 0.50 mm) appearing on the circumference shall be measured. Those to be included in the measurement shall be:

- (a) Those occurring between the oxide coating and the bond coat.
- (b) Those cracks occurring within the oxide coating .

5.1.2 Test Button Crack Total. For each test button, the measurements of each crack shall be totaled and noted for that test button. This measurement shall be divided by the circumference of the test button and expressed in percentage as follows:

$$\frac{\text{Crack Total}}{\text{Button Circumference}} \times 100 = \text{Percent}$$

AIRCRAFT ENGINE BUSINESS GROUP  
*Specification*

SPECIFICATION NO. F50TF60  
ISSUE NO. 1(T)  
DATE March 10, 1986  
PAGE 6  
FSCM 07482  
SUPERSEDES \_\_\_\_\_  
NEW

TEMPORARY SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the requirements specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until the "S1" issue is published.

PLASMA SPRAYED YTTRIA STABILIZED ZIRCONIA COATING  
(Ni-Cr-Al-Y BOND COAT)

1. SCOPE

1.1 Scope. This specification presents requirements for a two layered plasma sprayed coating consisting of a Ni-Cr-Al-Y bond coat plus a Yttria stabilized Zirconia top coat used for ceramic shrouds.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified, the requirements herein apply to all classes.

CLASS A:

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Capability - The words, "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

Coating Lot - All coated parts produced in a single production run from the same batch of raw materials under the same fixed conditions and submitted for inspection at one time.

Powder Lot - A quantity of powder produced from the same raw materials, blended, and presented for inspection at one time.

Purchaser - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

PREPARED <i>Jim Johnson</i>	REVIEWED <i>W. H. Nelson 2/27/86</i>	APPROVED BY:
APPROVED <i>Sam M. [unclear] 2/27/86</i>	DISTRIBUTION <i>10A</i>	<input checked="" type="checkbox"/> EVENDALE <input checked="" type="checkbox"/> LYNN

GT9020-7 (4-85)

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2.1 Issues of Documents. The following documents shall form a part of this specification to the extent specified herein. Unless otherwise specified, the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM B 328	Density and Interconnected Porosity of Sintered Powder Metal Structural Parts and Oil Impregnated Bearings (VOL. 02.05)
ASTM E 18	Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials (02.03, 03.01)

GENERAL ELECTRIC SPECIFICATIONS

A50TF240	Zirconium Oxide Yttrium Oxide Powder
E50TF424	Thermal Shock Jets Test Method for Ceramic Shrouds
B50TF192	Nickel-Chromium-Aluminum-Yttrium Alloy Thermal Spray Powder (NiCrAlY)
E50TF121	Erosion Test Method For Compressor Clearance Control Coatings
P28TF2	Thermal Spray Operator and Equipment Qualification

GENERAL ELECTRIC PHOTOGRAPHS

8602008	Maximum Acceptable Porosity And Oxides At The Bond Coat/Substrate Interface.
8602009	Maximum Acceptable Porosity /Layer Lines In The bond Coat
8602010	Maximum Acceptable Porosity/Layer Lines In The Oxide Top Coat.
8602011	Maximum Acceptable Unmelted Particles In The Bond Coat

3. REQUIREMENTS

3.1 General

3.1.1 Technical Plan. A process technical plan shall be prepared for each part number in accordance with P1TF33, CL-A, and shall be submitted by the coating vendor and approved by the Purchaser prior to coating parts.

3.1.1.1 Multi-Surface Coverage Requirements. When coating is required on more than one continuous surface of a part, the process for each separate surface shall be included in the technical plan.

3.1.2 Equipment And Operator Qualification. The equipment and operators used in applying the coatings shall be qualified and the coating schedule certified in accordance with P28TF2, CL-A.

3.1.3 Surface Requirements. When coating is required on more than one surface of a part, property requirements for each separate surface shall conform to all requirements of this specification.

3.1.3.1 Test Sample Surface Representation. One test button may qualify a part containing more than one surface provided the distance between individual surfaces and the spray nozzle does not vary more than  $\pm 0.25$  inch (6.35 mm).

### 3.2 Coating Material

3.2.1 Coating Materials. The coating materials shall be as follows:

#### Bond Coat

B50TF192 CL-A

#### Top Coat

A50TF240 CL-A

3.3 Powder Lot Qualification. Prior to the use of each new lot of powder for bond coat and top coat, test samples coated in accordance with the technical plan shall meet the requirements of this specification. Powder lots showing conformance shall be used for coating parts.

3.4 Coverage. The coating shall exhibit complete coverage in the areas specified for coating on the part drawing. There shall be no coating on areas other than those specified on the part drawing.

3.4.1 Surface Condition. The as-sprayed coating shall be uniform and free from cracks, blisters, chipping and flaking.

3.4.2 Adhesion. The coating shall exhibit no spalling or lifting.

### 3.5 Bond Coat

3.5.1 Bond Coat Thickness. The as-sprayed bond coat thickness shall be as specified on the part drawing.

3.5.2 Bond Coat/Substrate Porosity And Oxides. Porosity and oxides at the bond coat and substrate interface examined at 200X shall not exceed that of photograph 8602008

3.5.3 Bond Coat Porosity. Porosity in the bond coat examined at 200X shall not exceed that of photograph 8602009

3.5.4 Bond Coat Layer Lines. Layer lines within the bond coat examined at 200X shall not exceed those of photograph 8602009.

3.5.5 Unmelted Particles (Bond Coat). Unmelted particles within the bond coat examined at 200X shall not exceed those of photograph 8602011.

### 3.6 Top Coat

3.6.1 Top Coat Thickness Tolerance. The as-sprayed top coat thickness for parts and test panels shall not exceed +0.010", -0.000" of the thickness requirements specified on the drawing.

3.6.2 Top Coat Porosity. Porosity in the oxide top coat examined at 200X shall not exceed that of photograph 8602010.

3.6.3 Top Coat Layer Lines. Layer lines within the oxide top coat examined at 200X shall not exceed those of photograph 8602010.

3.6.4 Top Coat Density. The density of the free standing oxide layer when determined in accordance with ASTM B 328 shall be between 5.16 to 5.4 grams per cubic centimeter.

3.6.4.1 Density Panel Preparation. The density test panel may be processed with or without bond coat and a minimum of panel surface preparation.

3.6.4.2 Oxide Removal. The oxide layer may be removed from the metallic substrate by thermal shock or chemical strip.

3.6.5 Top Coat Erosion. Erosion test will be performed on a minimum of one (1) panel in accordance with E50TF121 CL-A. Erosion factors (E#) shall be within the following limits:

E#                      5.0 - 10.0 Sec/Mil

3.6.7 Top Coat Surface Hardness. The Rockwell 30T hardness of the top coat surface shall have an average value of 85 minimum.

3.7 Metallographic Requirements. Metallographic evaluations shall be performed on heat treated and aged (as specified on the drawing) samples prepared for evaluation by a method approved by the purchaser.

3.8 Thermal Shock Resistance Requirements. Each coating lot of parts shall meet the following thermal shock requirements:

(a) Test buttons processed with each coating lot shall:

- (1) Not exhibit a combined crack length between the bond coat and the top coat or within the top coat in excess of 50% of the button circumference.
- (2) Exhibit no spallation of the top coat.
- (3) Exhibit no separation between the bond coat and the substrate.
- (4) Exhibit no extension of surface cracking down into linear circumferential cracking.

3.9 Recoating. Parts rejected because of discrepant coating shall have the coating stripped by a method approved by the Purchaser and shall be recoated in accordance with all of the requirements of this specification.

3.9.1 Recoated Parts. A part shall not be stripped and recoated more than twice. Stripped and recoated parts shall be identified on the certificate of test.

3.10 Test Specimens. Test specimens shall be processed with each coating lot and shall be placed in the same plane at the average distance from the spray nozzle as the surfaces being coated. The number and type shall meet the requirements of Table I.

TABLE I - Test Specimens (Minimum Quantity)

<u>QUANTITY</u>	<u>CONFIGURATION</u>	<u>MATERIAL</u>	<u>PURPOSE</u>
2	0.125" + 0.005"x1.0" Dia.	Identical to parts	JETS test
1	0.065" to 0.125"x1.0"x2.0" Panel	Approved by Purchaser	Erosion Test
1	0.065" to 0.125"x2.0"x2.0" Panel	Approved by Purchaser	Density
1	0.065" to 0.125"x0.625"x1.0" Panel	Approved by Purchaser	Metallography

3.11 Certificate of Test. The coating vendor shall furnish a certificate of test with each lot of coated parts. The certificate shall include the numerical results of all required tests and inspections and shall show that the results are in accordance with the requirements of this specification. Parts which have been reworked shall be identified. The certificate shall be mailed by the coating vendor to the Purchaser with or preceding the shipment of parts. The certificate of test shall also contain the following information.

- (a) Purchase order number
- (b) Part drawing number
- (c) Quantity of parts
- (d) This GE specification number, class and revision number
- (e) Powder manufacturer's name and powder lot number

#### 4. QUALITY ASSURANCE PROVISIONS

4.1 General. Coated parts shall be tested in accordance with a quality plan approved by the Purchaser to determine conformance with the requirements of this specification. The vendor quality plan shall include a minimum of three coating runs demonstrating acceptable coating characteristics on actual hardware along with test specimens from Table I. The test specimens from Table I will then be used for accepting subsequent coating runs.

4.2 Powder Lot Qualification. Each new lot of powder for bond coat and top coat shall be demonstrated capable of conforming to the requirements of this specification prior to coating parts.



## F50TF60-1(T)

4.3 Visual Inspection. Visual inspection of each coated surface shall be performed at 50X magnification.

4.4 Coating Thickness Determination. Thickness shall be determined at a minimum of three different locations on a coated part or flat test sample using flat anvil micrometer measurements. Flat test samples shall be of a material having a similar composition and hardness, prepared for coating in the same manner and positioned to received the same spray deposit as the part being sprayed. Other methods may be used if approved by the Purchaser.

4.5 Metallographic Evaluation. The vendor shall perform a metallographic evaluation on one (1) test panel from Table I at 200X magnification.

4.6 Density Determination. Density of the free standing oxide layer shall be determined in accordance with ASTM B 328.

4.7 Erosion Test. The erosion test shall be performed in accordance with E50TF121 CL-A.

4.8 Surface Hardness. The top coat surface hardness test shall be performed in accordance with ASTM E 18 on all quality control specimens using a superficial hardness tester.

4.8.1 Equipment Calibration. Hardness tester calibration shall be confirmed on standard block prior to each coating lot evaluation.

4.9 Thermal Shock Test. Thermal shock resistance shall be determined on a TS JETS tester in accordance with E50TF424 CL-A at an oxide thickness and surface temperature to be determined by the Purchaser.

## 5. PACKAGING

5.1 Packing. Coated parts shall be suitably packed to prevent damage or loss in shipment.

5.2 Marking. Each shipment shall be legibly marked with the purchase order number coating vendor's name, GE part designation, number of parts, this GE specification, class and revision number.

APPENDIX B

TECHNICAL PLAN FOR  
APPLYING CERAMIC COATING TO  
T700 HPT SHROUDS

June 1986

PREPARED BY:

B.K. Gupta, Mfg, Technology Engineer  
Advanced Coatings Programs  
GE MTL Coating Technology

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- 6.0 QUALITY ASSURANCE
- 7.0 SHIPPING

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## 1.0 SCOPE

- 1.1 This technical plan covers the process requirements for application of thermal barrier coating system (TBC) including bond coat and top coat to HPT shrouds of the T-700 engine.

P/N  
6064T52P03

Part Name  
HPT Shrouds

- 1.2 Deviations and/or changes to significant operations must be approved in writing and added to this technical plan as an amendment before implementing such changes.

### 1.3 Definitions

- 1.4.1 Air Plasma Spray (APS) - The process used to apply metallic and non-metallic materials in ambient atmospheric condition.
- 1.4.2 Overspray/Overcoat - Material deposited outside the prescribed area which is to be coated as per part drawing notes.
- 1.4.3 Masking - The procedure to prevent coating deposition outside the area which is to be coated as per drawing notes.
- 1.4.4 Lot - A group of not more than thirty (30) parts including Q.C. which are coated together in a spray run.
- 1.4.5 Q.C. Part - A HPT Shroud used to evaluate the coating quality including thickness, microstructure, adherence to the substrate and the coverage as per the drawing requirements.
- 1.4.6 Part - A T-700 HPT Shroud, P/N 6064T52P03.
- 1.4.7 Fixture - Tooling used to support the part while being coated.
- 1.4.8 Run - The coating of a lot of parts.
- 1.4.9 Purchaser - General Electric Aircraft Engine Business Group, T-700 Project Engineering.
- 1.4.10 Process Engineering - TBC Processing Engineering team of MTL/EMTL.
- 1.4.11 YSZ - Yttria Stabilized Zirconia material, A50TF240 Class A.

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- 1.4.12 Bond Coat - A metallic coating of nickel base alloy on the part, providing a rough surface.
- 1.4.13 Top Coat - A ceramic coating of YSZ on the part.
- 1.4.14 Pass - One complete traverse of the spray gun through airfoil surfaces designated to be coated.
- 1.4.15 M.R. - Materials reviewed by engineering personnel for disposition.

## 2.0 APPLICABLE DOCUMENTS

2.1 To the extent specified, the following documents form an integral part of the Technical Plan. Unless otherwise specified, the latest revision shall apply:

### 2.2 AEBG Specifications

2.2.1 P1TF33 - Preparation of Technical Plan

2.2.2 P10TF1 - Vacuum Heat Treating

2.2.3 F50TF60-1(T) - Plasma sprayed YSZ coating.

2.2.4 P28TF2 - Thermal Spray Operator and Equipment Qualification.

2.2.5 Top Coat Erosion - Erosion test specification E50TF121, Class A.

#### 2.2.6 General Electric Photographs

8602008 Maximum acceptable porosity & oxides at the bond coat/substrate interface.

8602009 Max. acceptable porosity/layer lines in bond coat.

8602010 Maximum acceptable porosity/layer lines in oxide top coat.

8602011 Max. acceptable unmelted particles in bond coat.

### 2.3 Equipment Operating Procedures

To the extent specified, the following documents shall form an integral part of the operating plan.

2.3.1 Start-up and Shut-down Procedures for 7M Plasma Spray System - MTL Operating Procedure #2966-8-002.

2.3.2 Thermal Spray Processes - Receiving, Spraying and Shipping Production parts - MTL Operating Procedure #2966-8-003.

2.3.3 Grit Blasting Engine Hardware - MTL Operating Procedure #2966-8-005.

### 2.4 Direct Materials

	<u>Material</u>	<u>Specification</u>	<u>Vendor Source</u>
2.4.1	NiCrAlY Powder	B50TF192	Union Carbide, Inc.
2.4.2	Zirconia-Yttria	ZrO <sub>2</sub> -8%Y <sub>2</sub> O <sub>3</sub> ; -200+325 mesh A50TF240 C1A	Zircoa Products, Corning Glass Works Corning, N.Y.



2.5 Support Materials

	<u>Material</u>	<u>Specification</u>	<u>Vendor/Source</u>
2.5.1	Isopropyl Alcohol		In-plant
2.5.2	Stainless Steel Foil	.005-.020" thick	In-plant
2.5.3	1,1,1 Trichlorethane		In-plant
2.5.4	Masking Tape		In-plant
2.5.5	Argon Gas	99.99 Purity	In-plant
2.5.6	Hydrogen Gas	99.99 Purity	In-plant
2.5.7	Nitrogen Gas	99.99 Purity	In-plant

### 3.0 EQUIPMENT

	<u>Item</u>	<u>Manufacturer</u>	<u>Model No.</u>
3.1	Vapor Hone	Hydrohone	H25
3.2	Powder Feeders	Plasmadyne	1250
3.3	Powder Oven	Fisher Scientific	
3.4	Ultrasonic Cleaner	Sonogen	LTH-80
3.5	Vacuum Furnaces	Abar	Capable of heat treating up to 2000°F and operating at $5 \times 10^{-4}$ torr or better.
3.6	Vapor Degreaser	Detrex	VS-800E
3.7	Plasma Spray Controller	Metco	
3.8	Plasma Spray Gun	Metco	7MB
3.9	Grit Blast	Clemco	Silverado

#### 4.0 MANUFACTURING

Detailed description of significant and non-significant operations are given in the approved Operation Sheets. Significant operations are listed sequentially here.

4.1	Receive and Inspect	010	Check for damages and past compliances or non-compliances.
4.2	Vapor Degrease	020	Remove oil from surfaces.
4.3	Preparation prior to TBC spraying	030-050	Clean flowpath and mask parts
4.4	Apply coating on flowpath	070	Apply bond coat and 0.012" top coat.
4.5	Vacuum Heat Treatment	080	Diffusion to improve bond coat integrity.
4.6	Top Coat Spray	090	To apply YSZ.
4.7	Age Heat Treatment	100	To age parts at $1550 \pm 25$ for 4 hours.
4.8	Quality Inspection	120	To evaluate parts per quality plan in Spec. F50TF60-1(T).

#### 5.0 MATERIAL HANDLING AND STORAGE

All materials including direct and supporting materials listed in 2.4 and 2.5 shall be handled and stored in accordance with approved quality plan, and AEBG environmental and hazardous material safety requirements. Special requirements for the storage and handling of materials which have direct impact on the product quality are described in detail.

- 5.1 NiCrAlY Powder shall be stored in designated storage areas. All powder cans shall have AEBG powder specification B50TF192C1 A, powder size distribution, manufacturers name and lot number. NiCrAlY has an unlimited shelf life, but all materials shall be used on a first received, first used basis. The powder cans shall be capped at all times.
- 5.2 Yttria Stabilized Zirconia Powder shall be stored in designated storage areas. All powder cans shall have AEBG powder specification powder A50TF240C1 A, size distribution, manufacturer's name and lot number. Powder shall be dried at 120°F for at least 24 hours before using. The powder has an unlimited shelf life, but all material shall be used on a first received and first used basis. Powder contaminated with chemicals and other contaminants shall be discarded. Powder contaminated with water shall require process engineering approval prior to use.

## 6.0 QUALITY ASSURANCE

### 6.1 Requirements

- 6.1.1 Control of this process shall be determined by the visual inspection of the final product after aging at 1550<sup>0</sup>F for 4 Hrs., in-process NDE process control and the evaluation of the Q.C. part(s) per ceramic coating process specification F50TF60-1(T).
- 6.1.2 Coating on the Q.C. part(s) shall be representative of the production parts.
- 6.1.3 At least one (1) Q.C. part shall be coated in one coating run.
- 6.1.4 All paperwork (coating log, certificates, metallographic evaluation records, etc.) shall be retained for five years and available for inspection by the Purchaser.
- 6.1.5 Parts failing to meet applicable pre-process drawing requirements or displaying abnormal surface conditions and physical damage shall be stored separately for Purchasing review and disposition by the Purchaser.

### 6.2 Quality Inspection

#### 6.2.1 Visual Inspection

- 6.2.1.1 Coverage - The coating shall exhibit complete coverage in the areas specified for coating in the part drawing. There shall be no coating on areas other than those specified on the part drawing.
- 6.2.1.2 Surface Condition - The as-sprayed coating shall be uniform and free from cracks, blisters, chipping and flaking.
- 6.2.1.3 Adhesion - The coating shall exhibit no spalling or lifting.

#### 6.2.2 Thickness Measurement

In process thickness control shall be achieved by determining coating thickness at a minimum of three different locations on a coated flat test sample using flat anvil micrometer measurements. Flat test samples shall be of a material approved by the purchaser.

## 6.3 Testing

### 6.3.1 Q.C. Parts

The Q.C. parts coated with the production parts shall be evaluated for microstructure and thicknesses of various coating layers by approved metallographic procedure.

#### 6.3.1.1 Bond Coat

- (a) The as-sprayed bond coat thickness shall be as specified on the part drawing.
- (b) Porosity and amount of oxide contamination at the bond coat and substrate interface examined at 200X shall not exceed that of photograph 8602008.
- (c) Bond coat microstructural quality with regard to porosity, layer lines, and unmelted particles shall be per photographs 8602009 and 8602011.

#### 6.3.1.2 Top Coat

- (a) The as-sprayed top coat thickness for parts shall not exceed +0.010", -0.000" of the thickness requirements specified on the drawing.
- (b) Top coat porosity and layer lines examined at 200X shall not exceed those of photograph 8602010.

6.3.1.4 If Q.C. fails quality requirements, one repolish of the mount is allowed.

6.3.1.5 If re-evaluation of the Q.C. fails to meet coating structure requirements, then an additional part can be selected. If the additional Q.C. is acceptable, then whole lot represented by Q.C. is acceptable.

6.3.1.6 The metallographic specimens shall be examined at minimum magnification of the 200 X to determine conformance to the thickness requirements.

6.3.1.7 Repolish and additional Q.C. evaluation allowed, if Q.C. from a coating lot fails to meet thickness requirements.

#### 6.3.2 Test Samples

Each coating lot of parts shall include test samples which shall be placed in the same fixture and at the same average distance from the spray nozzle as the surfaces being coated. The number and type shall meet the requirements as specified in F50TF60-1(T).

6.3.2.1 JETS Test - Two test buttons processed with each coating lot shall be evaluated in JETS test. The test buttons shall meet the thermal shock life requirements as specified in F50TF60-1(T).

6.3.2.2 Erosion Test - Erosion test will be performed on a minimum of one (1) panel in accordance with E50TF121 Class A. Erosion factors (E#) shall be within the limits 5.0 - 10.00 sec/mil.

6.3.2.3 Density - The density of the free standing oxide layer when determined in accordance with ASTM B328 shall be between 5.16 to 5.4 grams per C.C.

#### 6.4 Rework

Parts not meeting quality requirements because of discrepant coating including top coat and bond coat shall be reworked per a method approved by the Purchaser and shall be recoated per an approved Operation Plan. The parts shall not be stripped and recoated more than twice. Stripped and recoated parts shall be recorded in the logbook and identified on the routing cards.

#### 6.5 Material and Equipment Control

6.5.1 To ensure quality of the powder materials used in the application of the coatings covered by the Technical Plan, all powders and other materials shall be purchased to the specifications from a purchaser-approved source.

6.5.2 Each new lot of powder for bond coat and top coat shall be capable of conforming to the requirements of this specification prior to coating parts.

6.5.3 Calibration of the equipment shall be carried out as specified in QA provisions of specification F50TF60-1(T).

6.5.4 All controls shall be set and the readings recorded in the coating log as defined in the approved operation sheets.



- 6.5.5 Dynamic process variables for the APS process shall be recorded at specified time intervals per purchaser approved plan. APS data including primary gas flow rate, secondary gas flow rate, plasma current and voltage shall be manually recorded in the process log book at least twice per run.
- 6.5.6 All heat treatment furnace controls shall be set and the reading recorded as defined in the approved operation sheets.
- 6.5.7 All relevant data, as indicated in the operation sheets shall be maintained for review by the purchaser.

## 7.0 SHIPPING

- 7.1 Parts shall be packaged and shipped in such a manner as to avoid and prevent physical damage and contamination with undesirable substances.
- 7.2 Parts shall be shipped in purchaser-approved containers and per purchaser approved packaging procedures.